Understanding, modelling and forecasting the climate response to volcanic eruptions

M. Ménégoz, C. Cassou, D. Swingedouw, R. Bilbao, O. Bellprat, F. Doblas-Reyes

Introduction

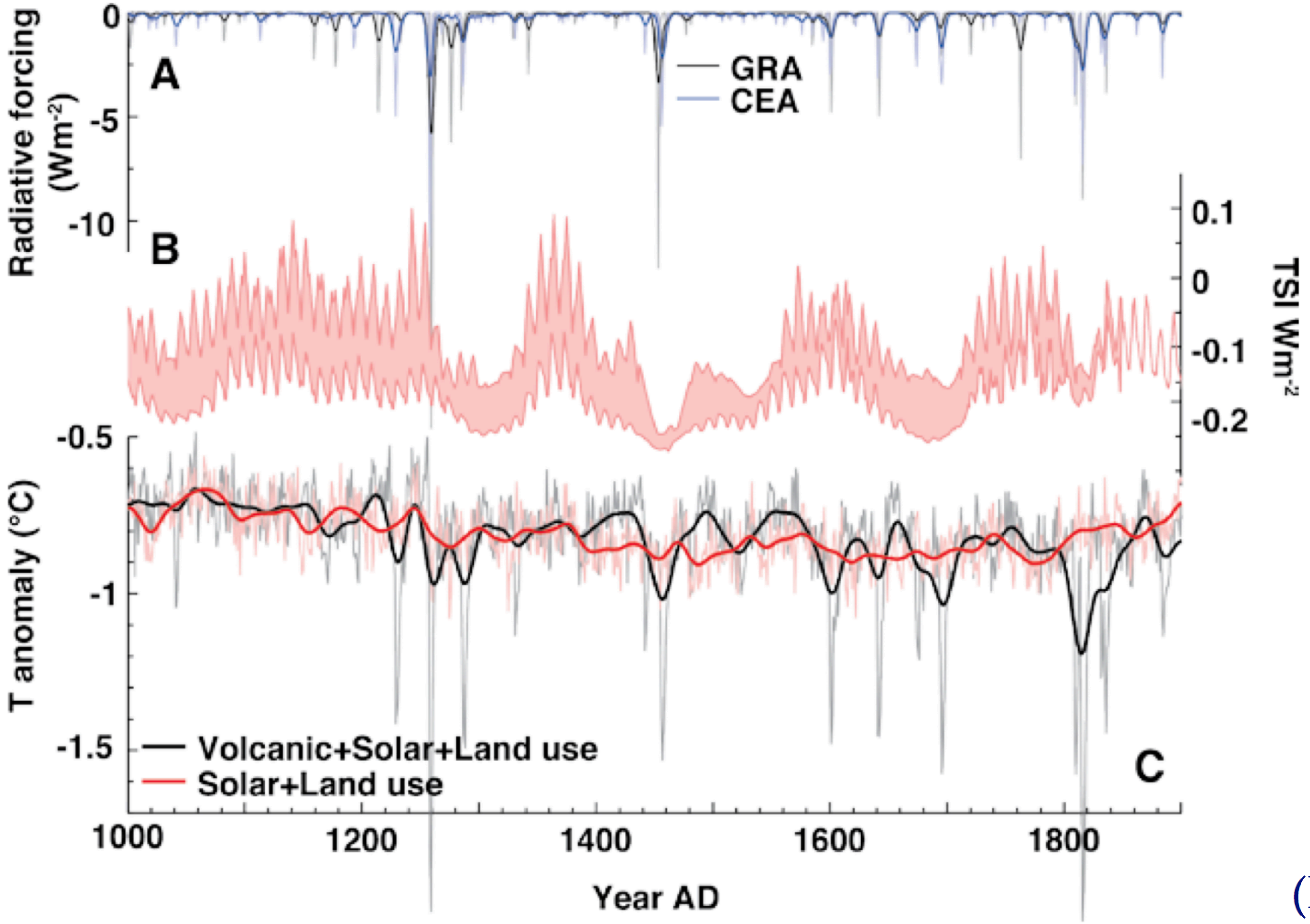
→ **The Agung 2017 eruption**

→ **100 000 persons evacuated**
→ **air transport affected**
→ **currently 1000 times smaller than the 1963 eruption**

(November, 27^{th}, 2017)

Introduction

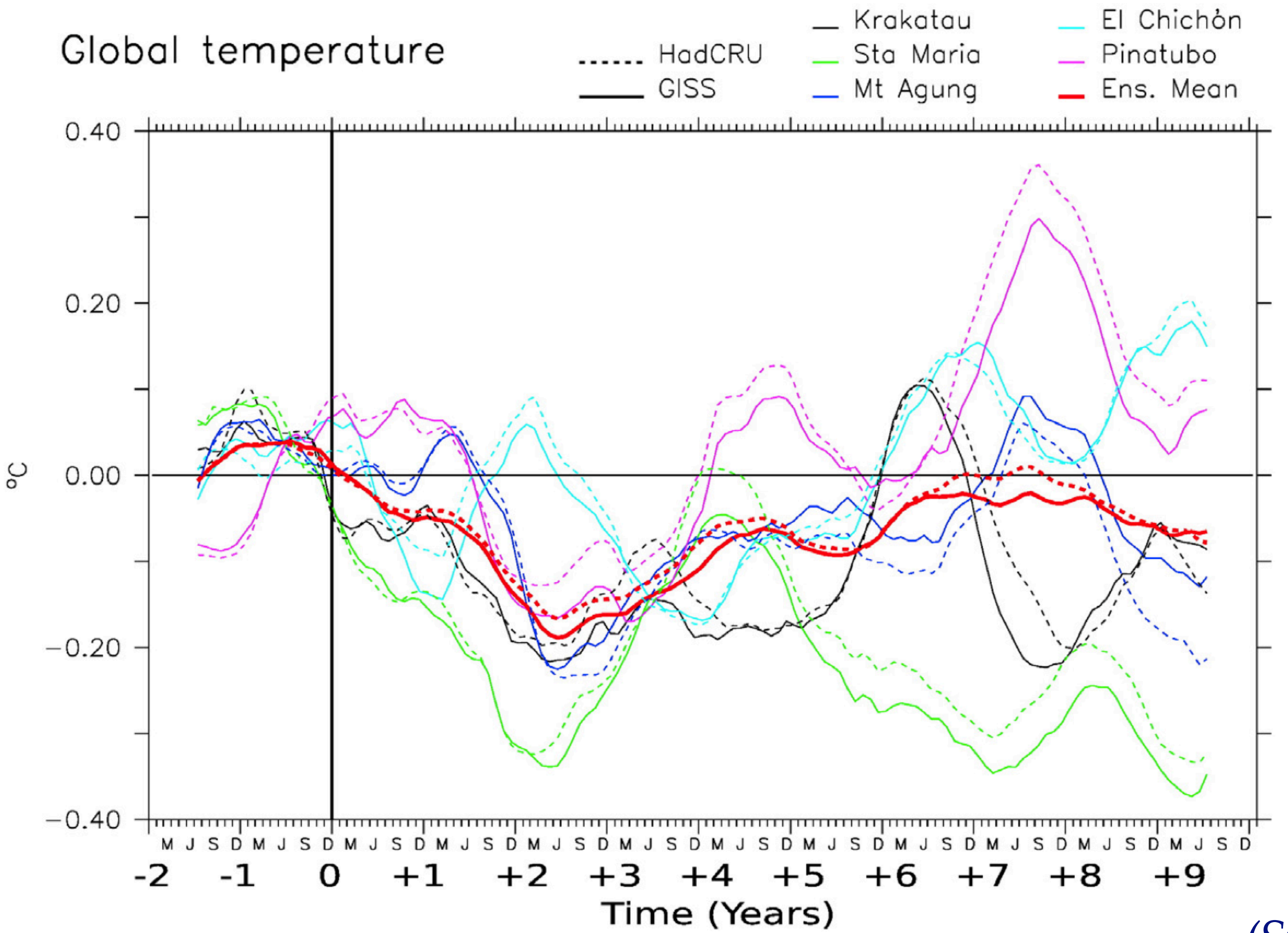
→ **Global cooling after volcanic eruptions**



(PAGES, 2015)

Introduction

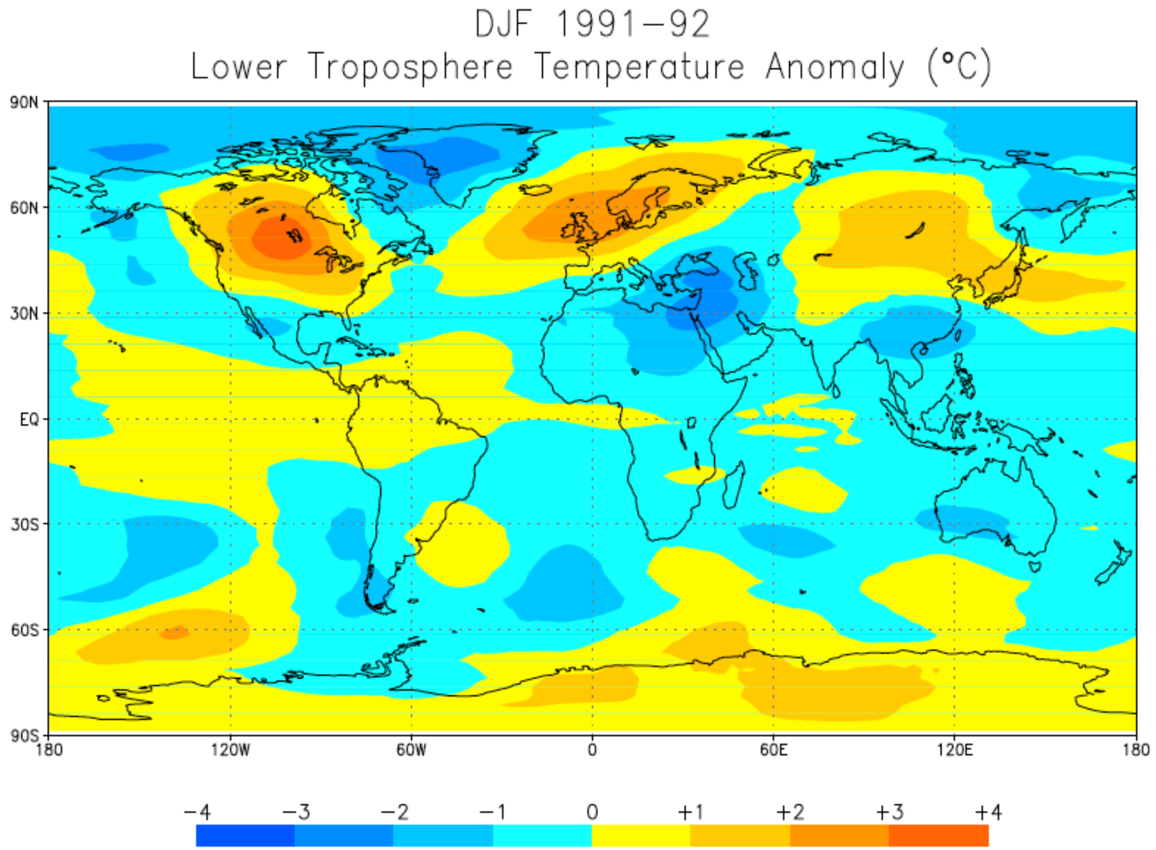
→ Global cooling



(Swingedouw et al., 2017)

Introduction

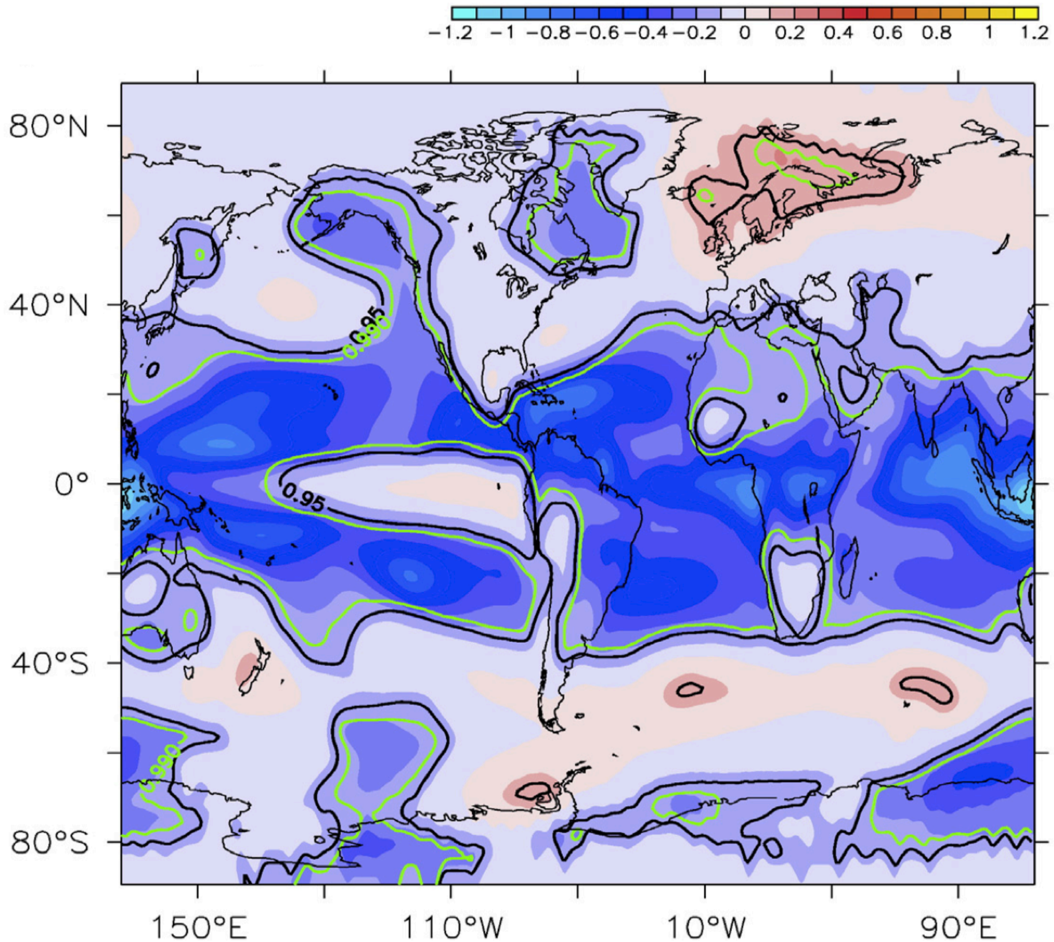
→ Global cooling but regional warming?



(Temperature anomaly observed in the lower troposphere the first winter after the Pinatubo eruption, Robock, 2015)

Introduction

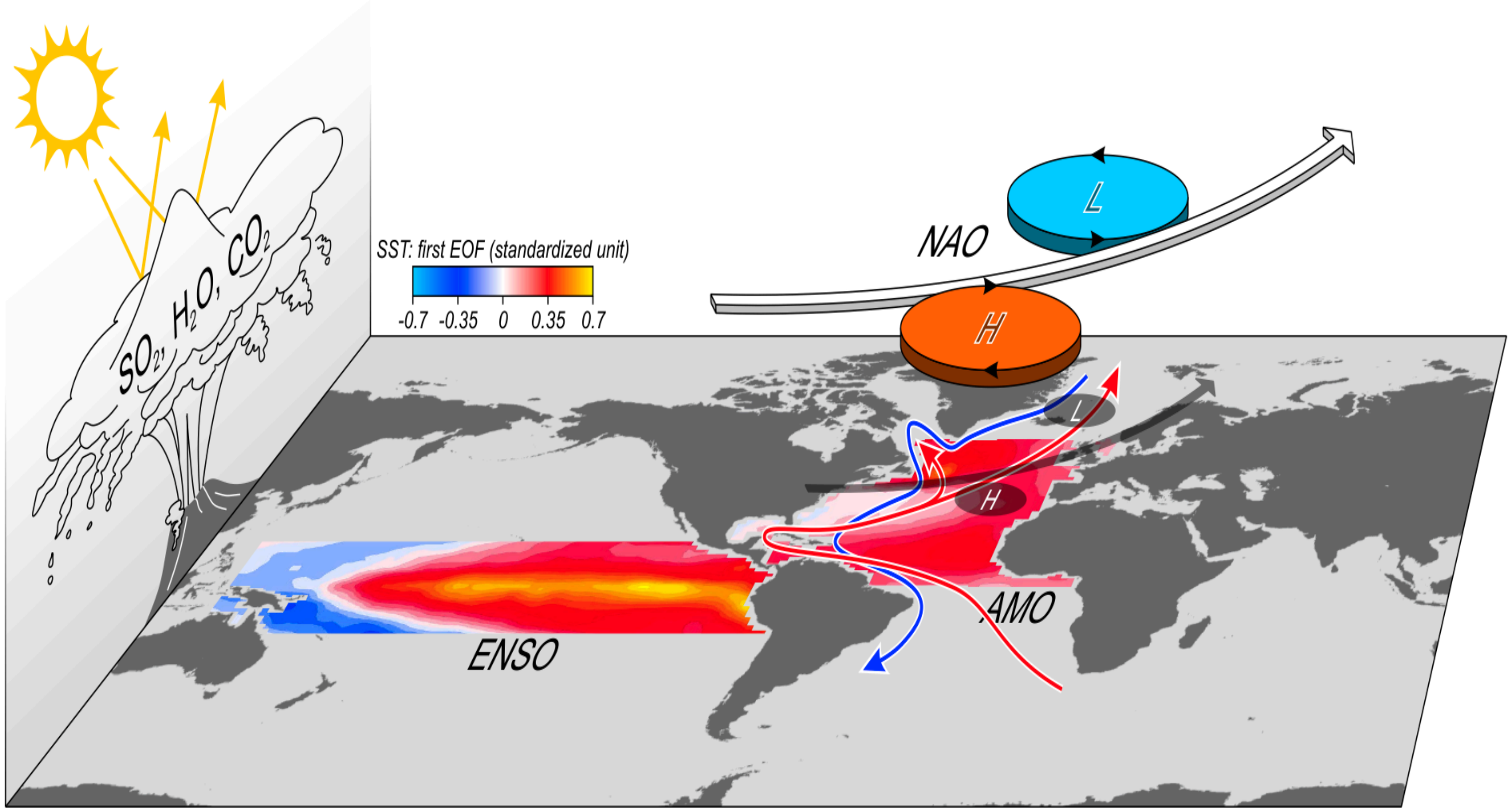
→ **Global cooling but regional warming?**



Composite of two-meter temperature modelled with CNRM-CM3 for the 19 eruptions larger or equal to the Pinatubo over the last millennium, in terms of the duration of the aerosol imprint in the atmosphere. (Swingedouw et al., 2017)

Introduction

→ **Dynamical signals?**



Impact of explosive volcanic eruptions on the main climate variability modes, Swingedouw et al., review for *Global and Planetary Change, 2017*

→ Introduction

→ **Do volcanic eruptions affect the NAO?**

→ Can we forecast the climate response to volcanic eruptions?

NAO and volcanoes

→ Positive NAO conditions observed during the two winters following the Pinatubo eruption…

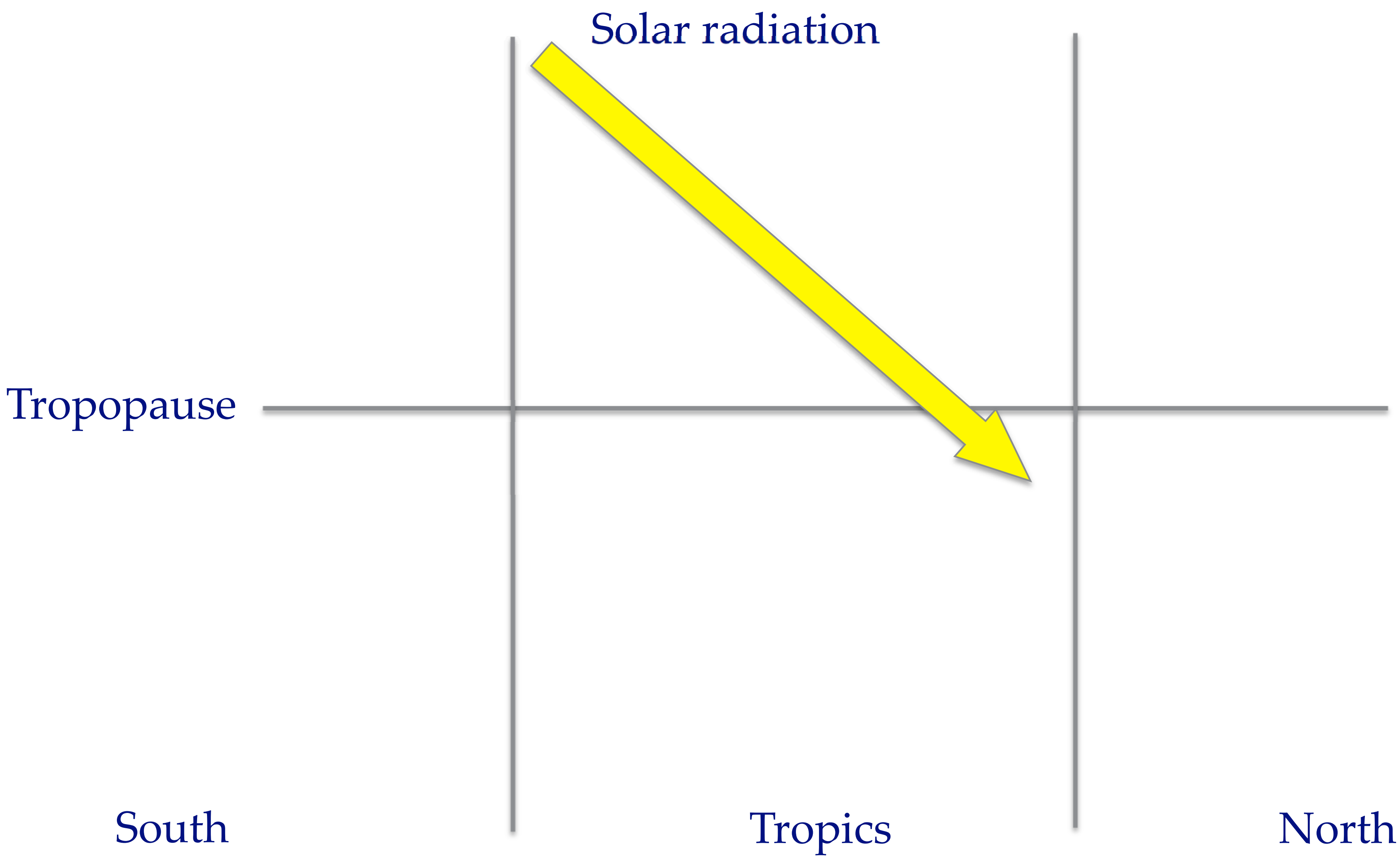
NAO and volcanoes

→ Positive NAO conditions observed during the two winters following the Pinatubo eruption in 1991…

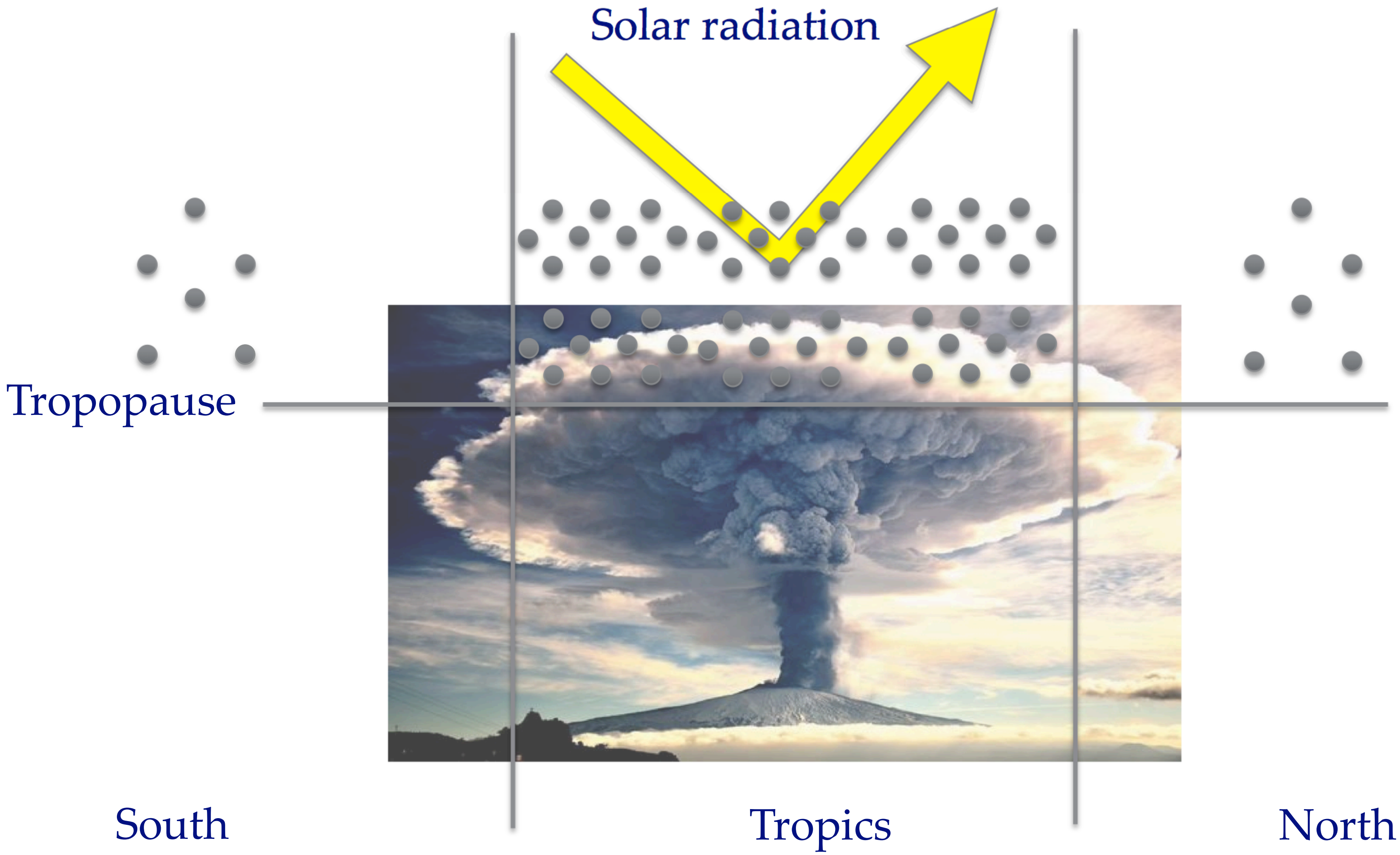
and

… the beginning of a passionate (and unclosed) debate!!!

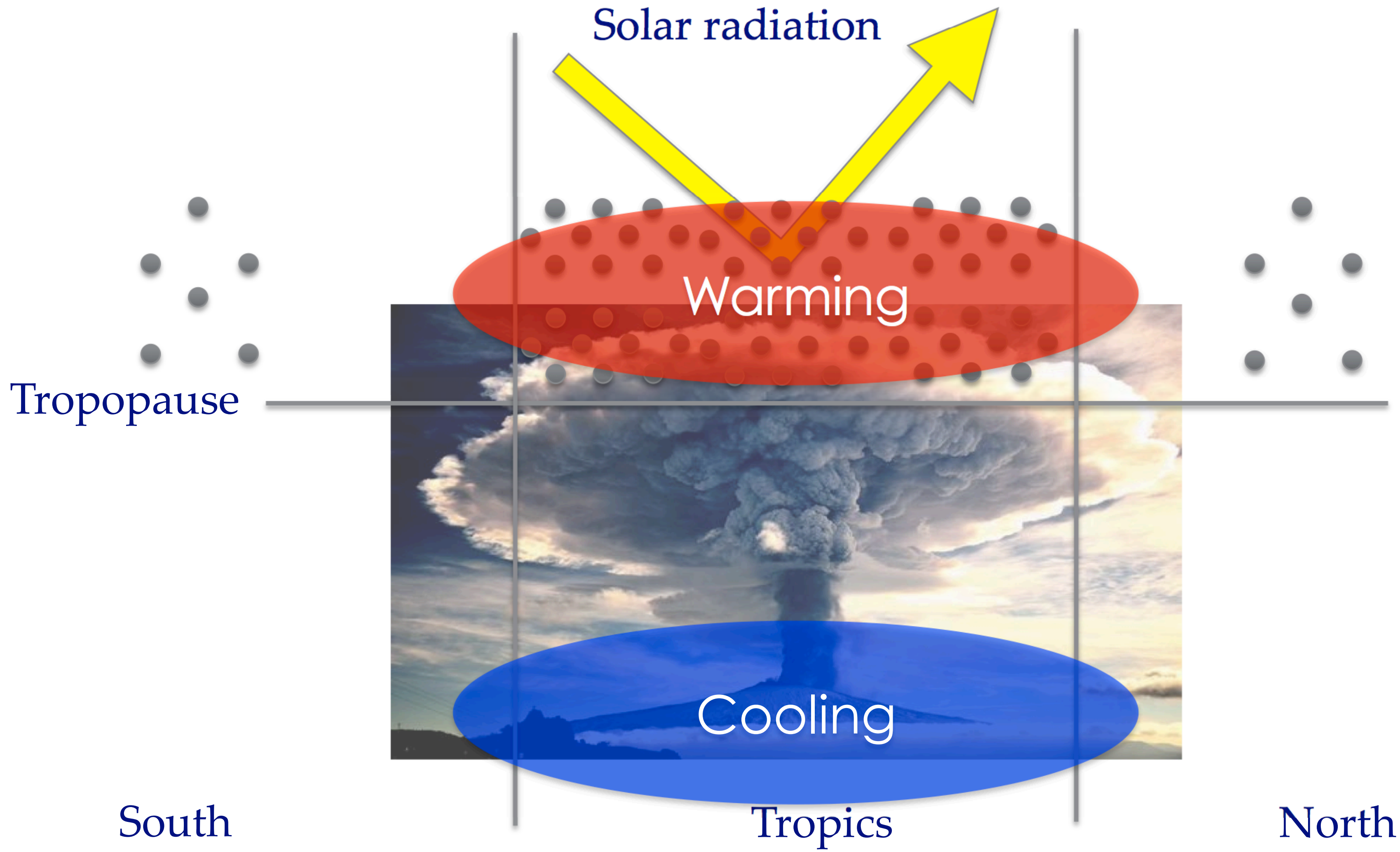
Mechanisms



Mechanisms

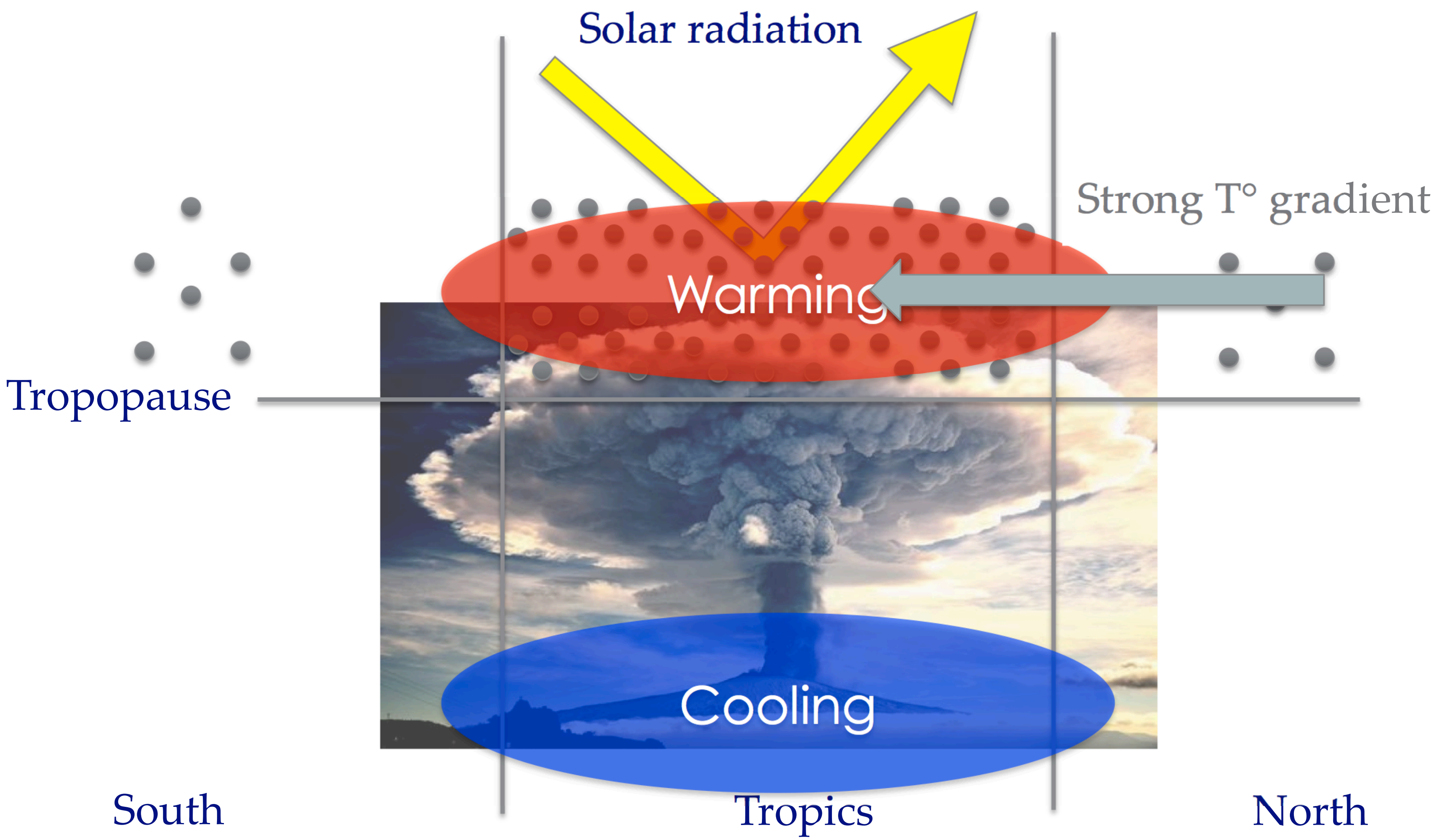


Mechanisms



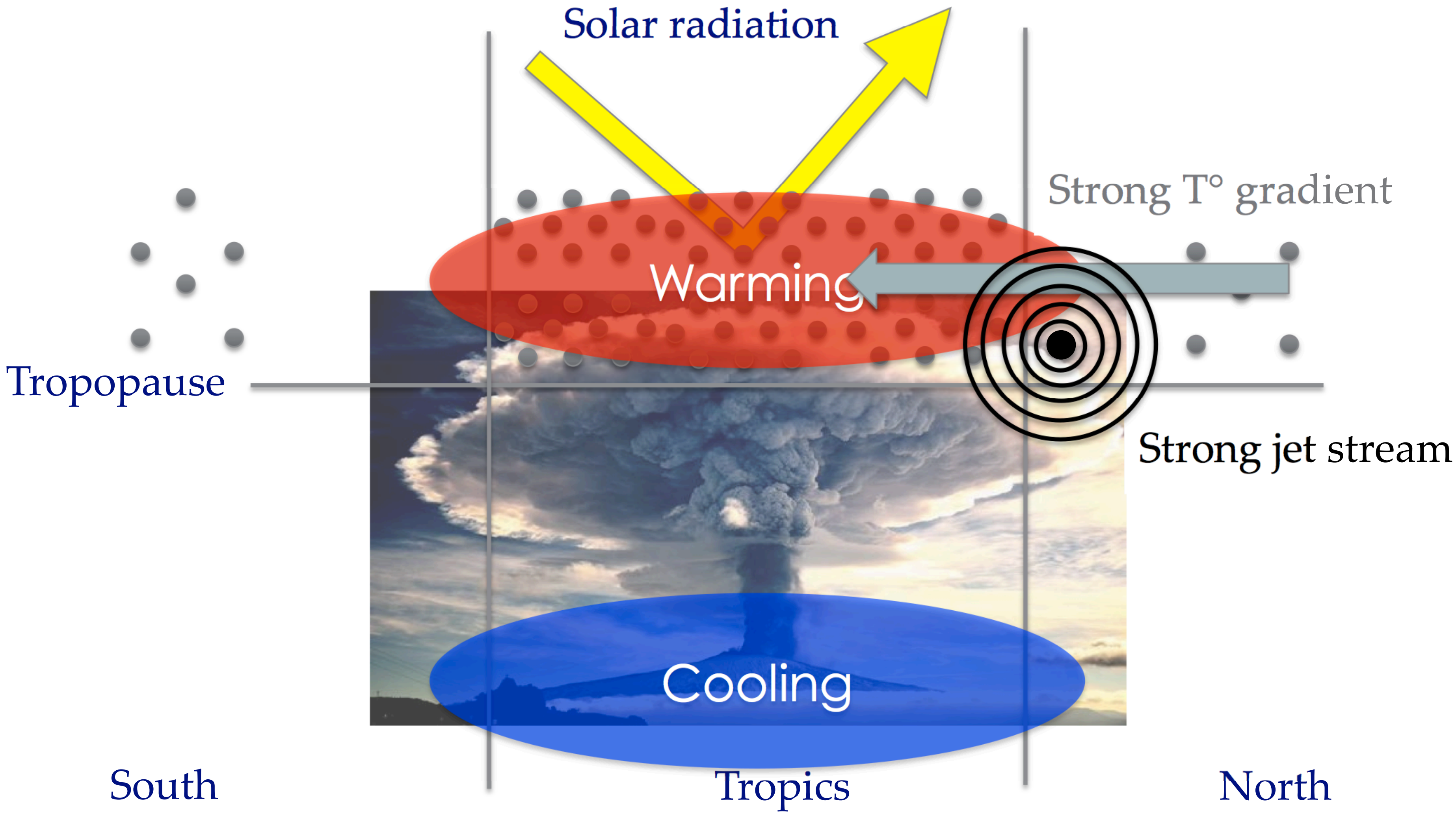
Solar radiation
Warming
Tropopause
Cooling
South
Tropics
North

Mechanisms



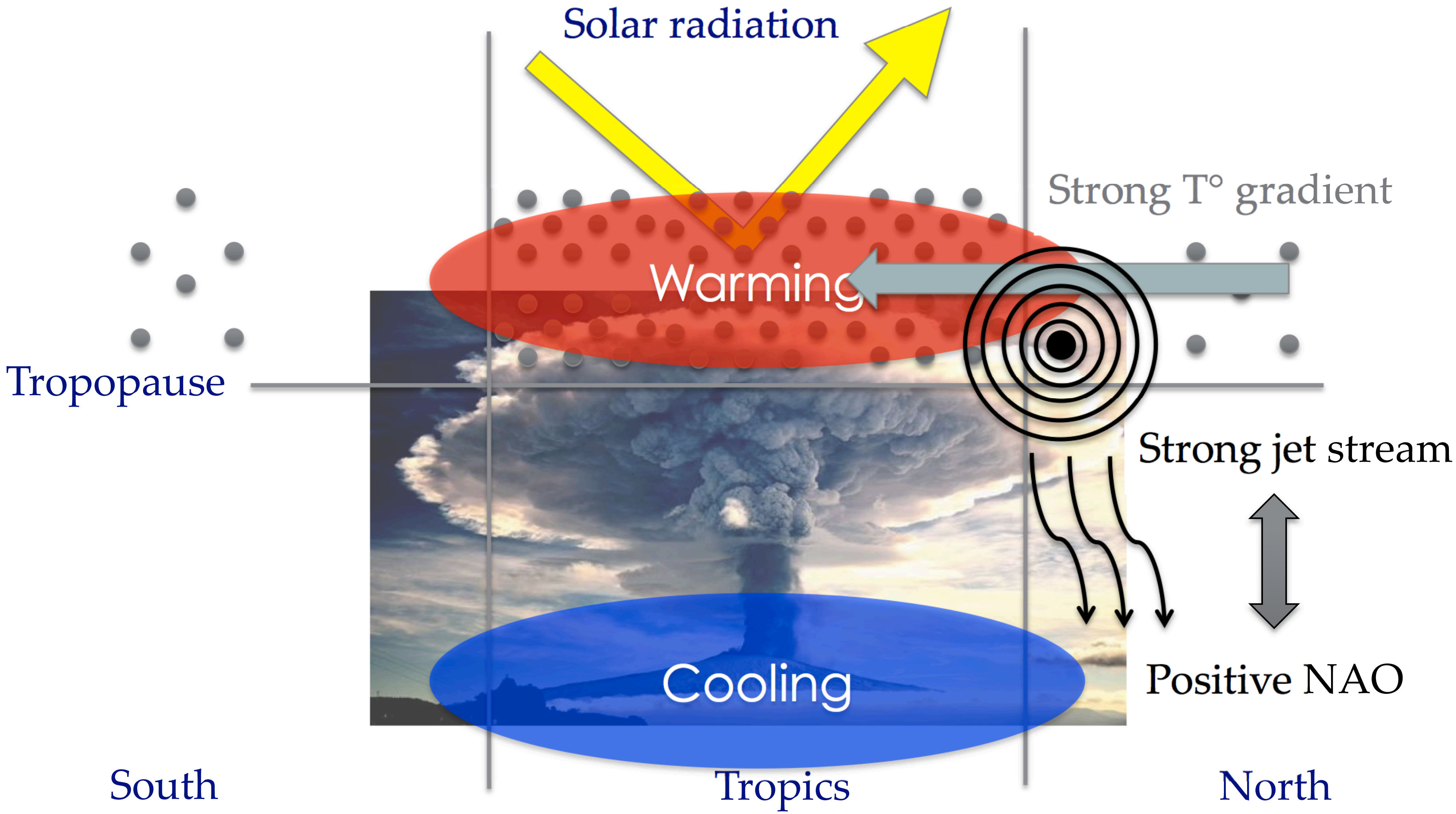
Solar radiation
Strong T° gradient
Warming
Tropopause
Cooling
South
Tropics
North

Mechanisms



Solar radiation
Strong T° gradient
Warming
Tropopause
Strong jet stream
Cooling
South
Tropics
North

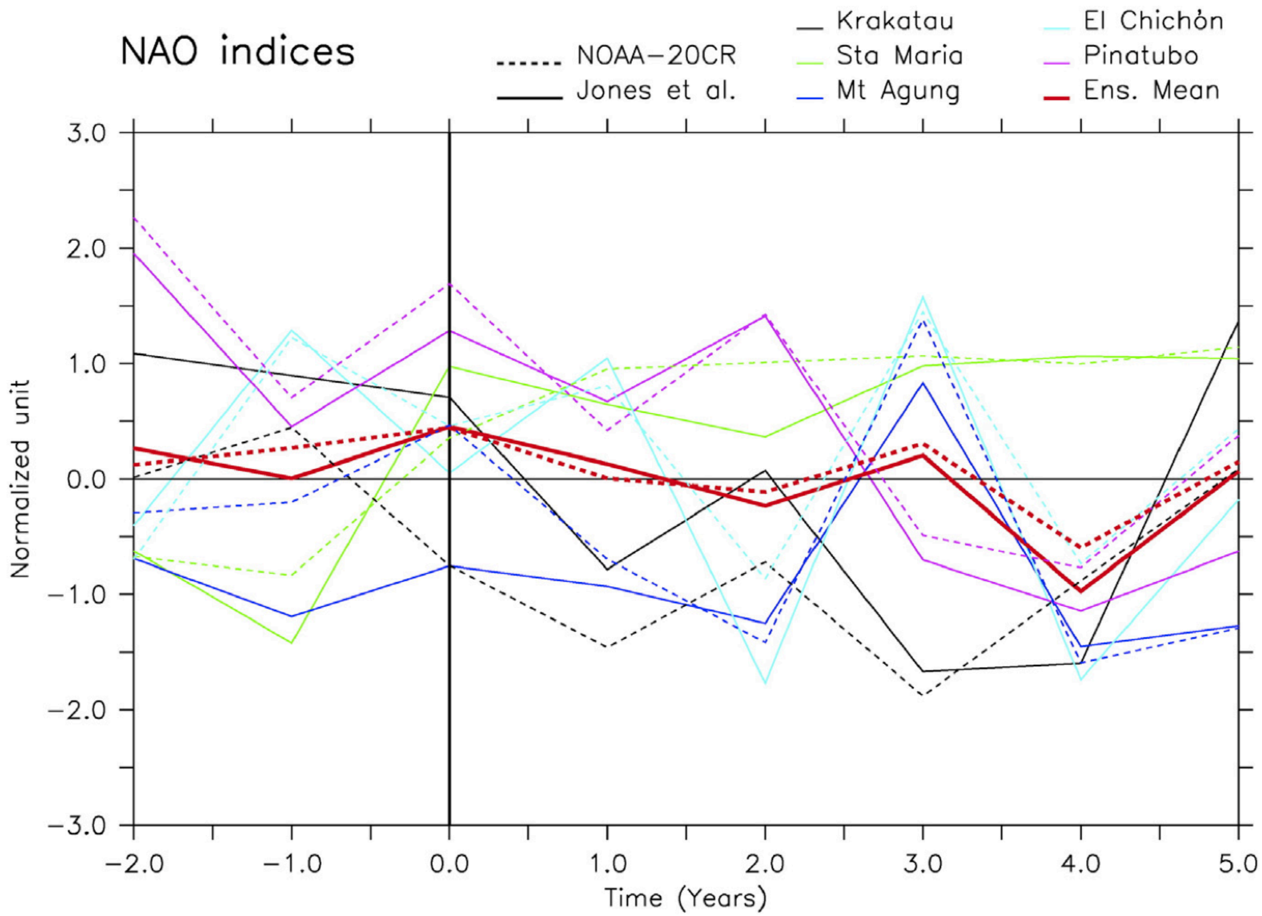
Mechanisms



Solar radiation
Strong T° gradient
Warming
Tropopause
Strong jet stream
Cooling
Positive NAO
South
Tropics
North

Observations

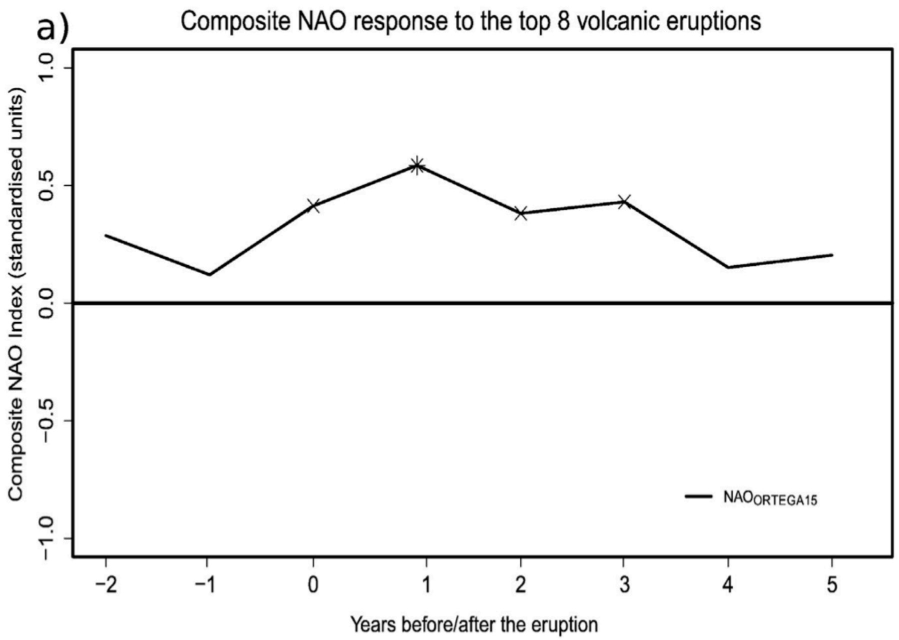
→ No evidence for any winter NAO signal after the last five major eruptions!



(Swingedouw et al., 2017)

Observations

→ **But positive NAO signal after the 8 major eruptions of the last 1000 years (very large eruptions, stronger than the Pinatubo)**



Observations

(Ortega et al., 2015; Swingedouw et al., 2017)

Observations

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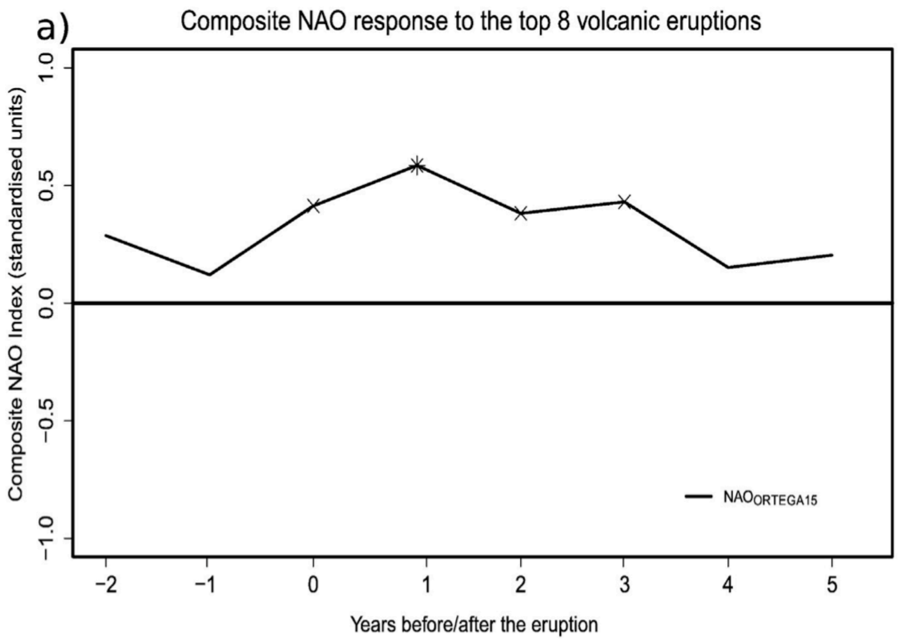
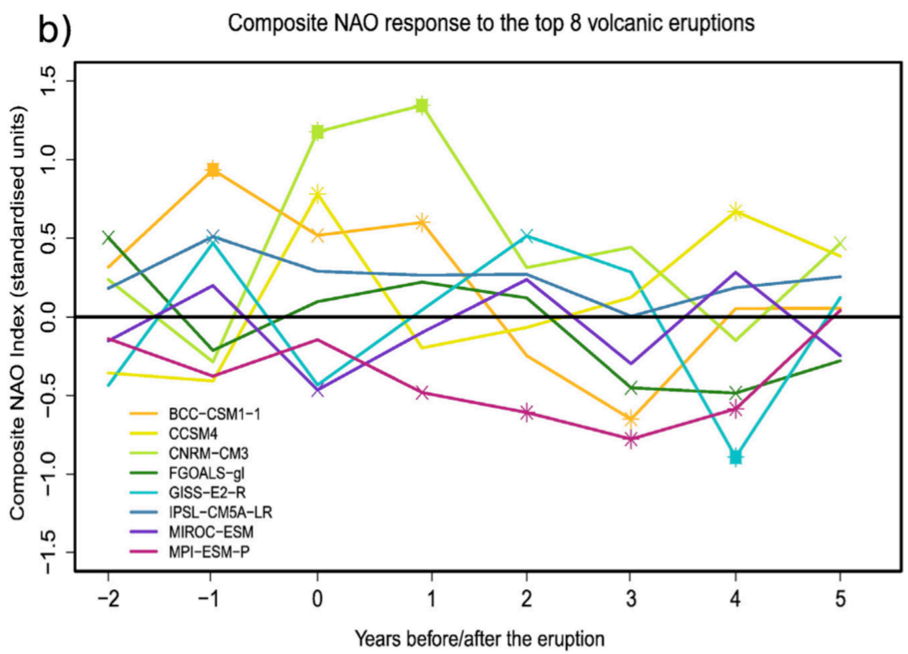


Observations



Not reproduced by all the models!

(Ortega et al., 2015; Swingedouw et al., 2017)

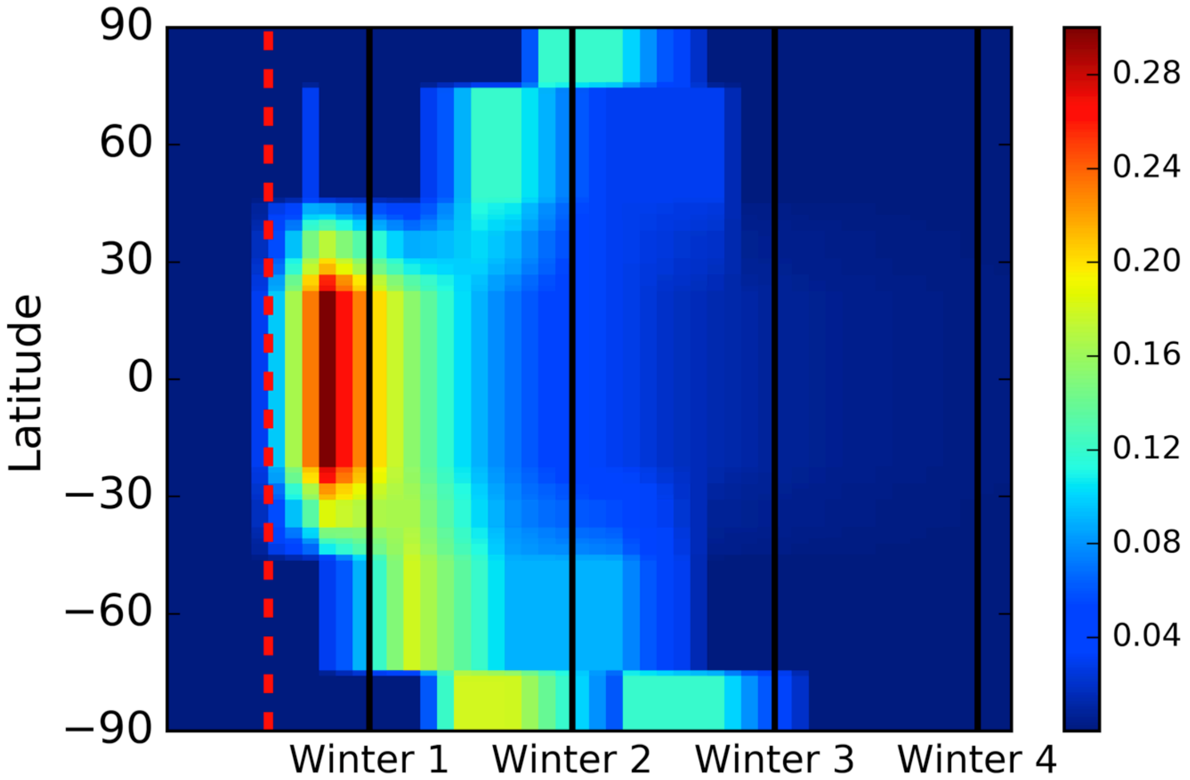
Model experiments

→ **Can we detect this signal from the internal variability?**

→ **Does the NAO response depend on the climate conditions in the Atlantic?**

Model experiments

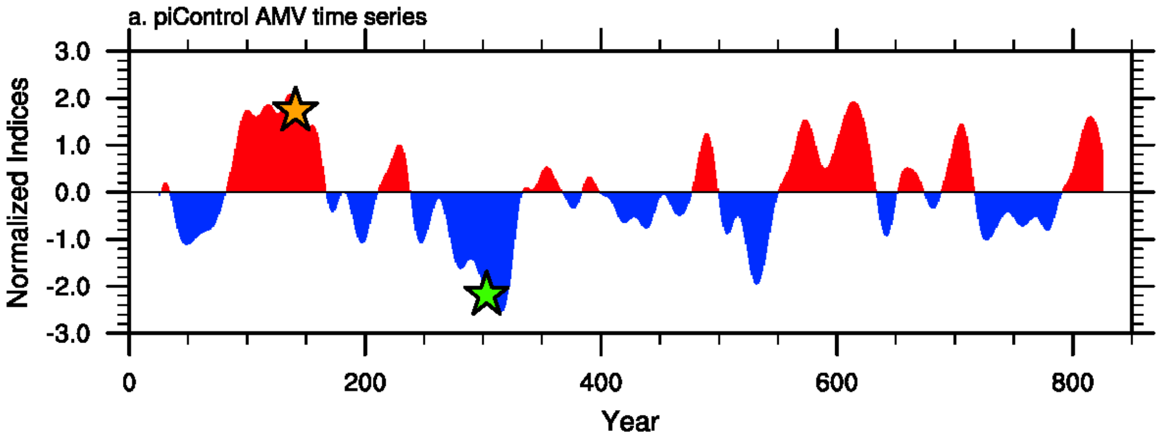
→ The Pinatubo forcing



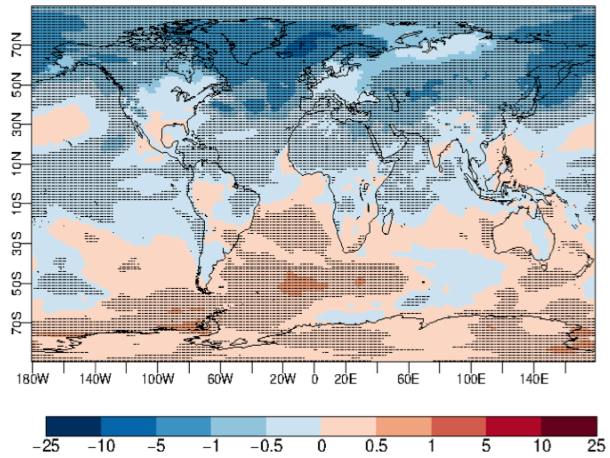
AOD at 550 nm observed after the Pinatubo eruption, Sato et al. (1993)

Model experiments

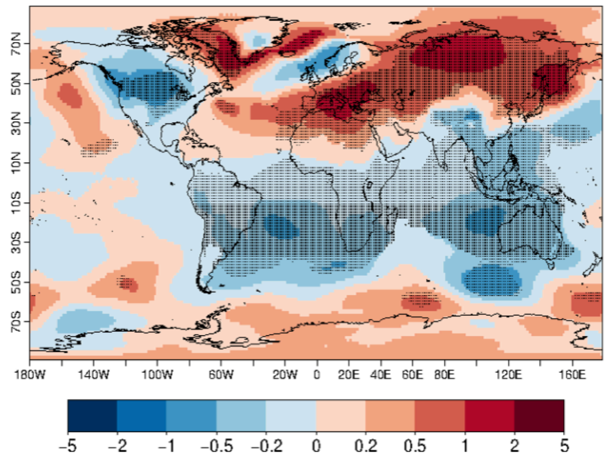
→ 850 years control experiment



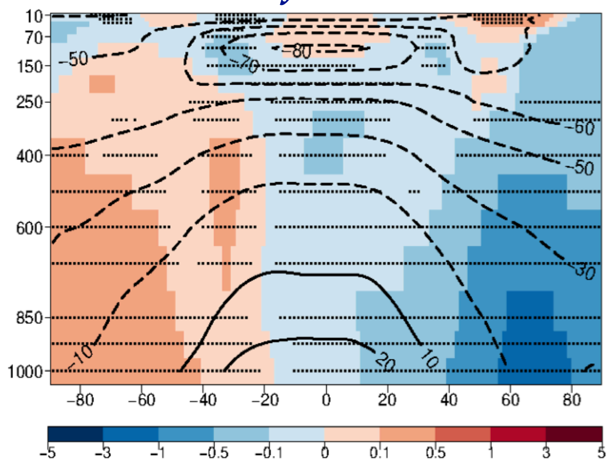
AMV- versus AMV+



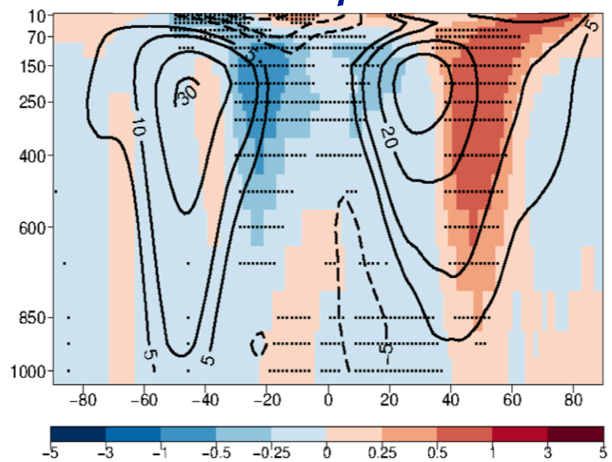
Surface T°



Sea level pressure



Zonal mean temperature

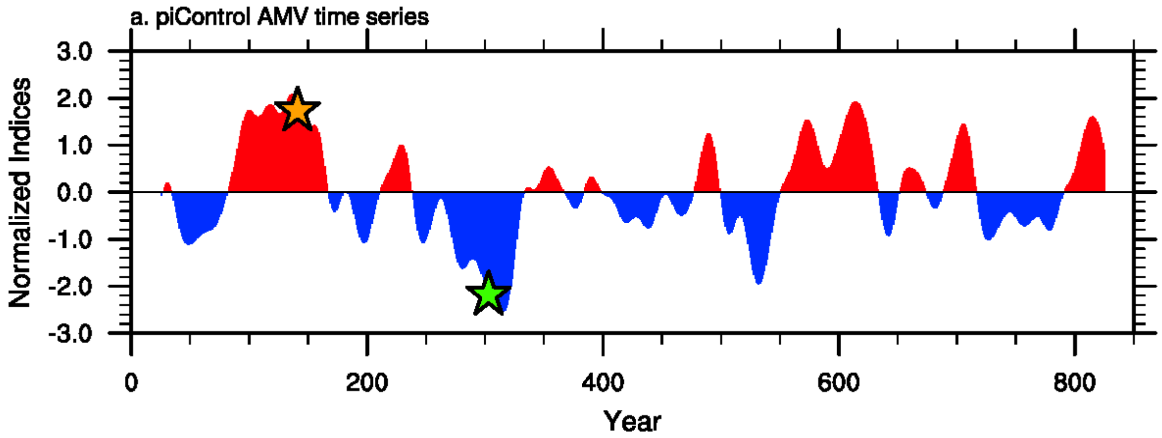


Zonal mean wind

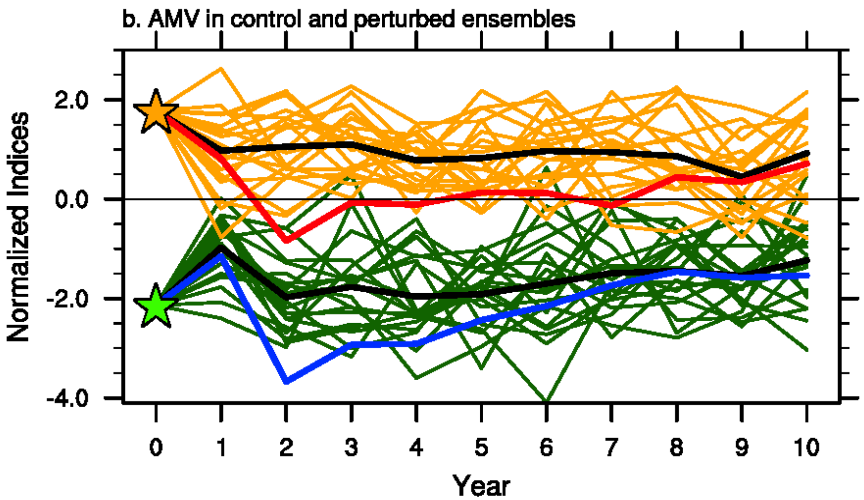
Winter ensemble mean differences between simulations run under warm and cold AMO conditions (36 members)

Model experiments

→ 850 years control experiment

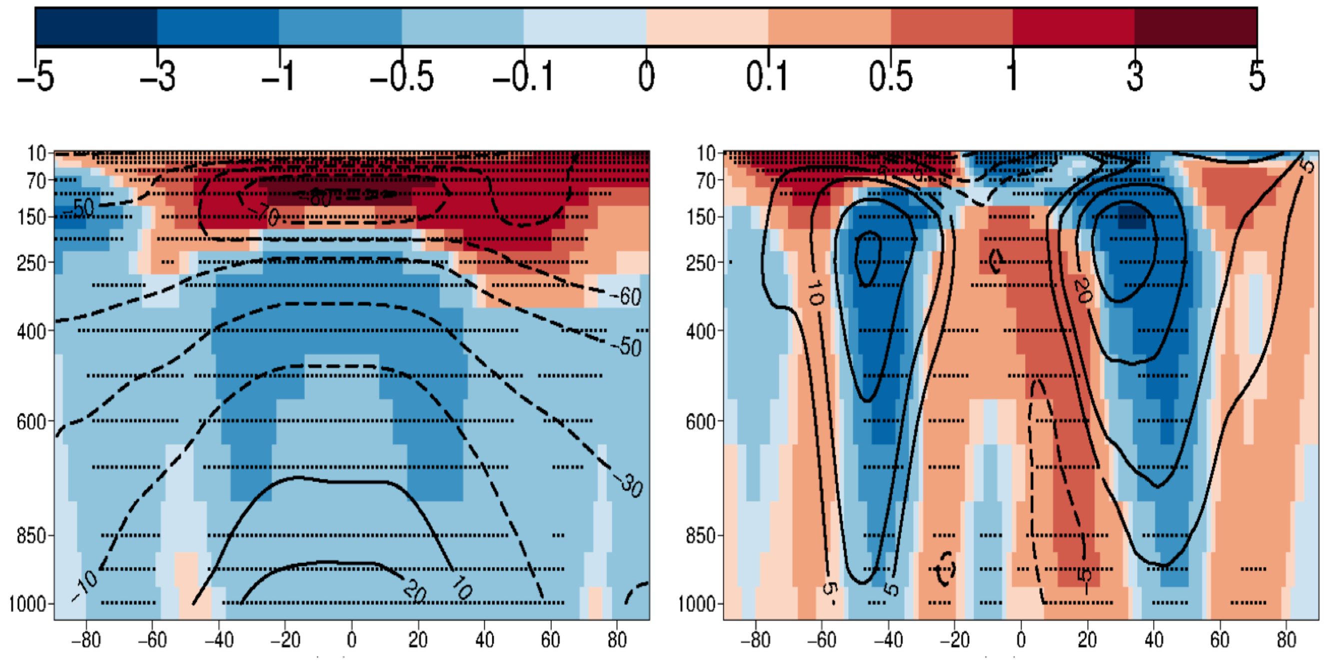


→ Simulating a Pinatubo under warm/cold phases of the AMV



Volcanic signal

First winter anomalies after a Pinatubo eruption, cold AMV case

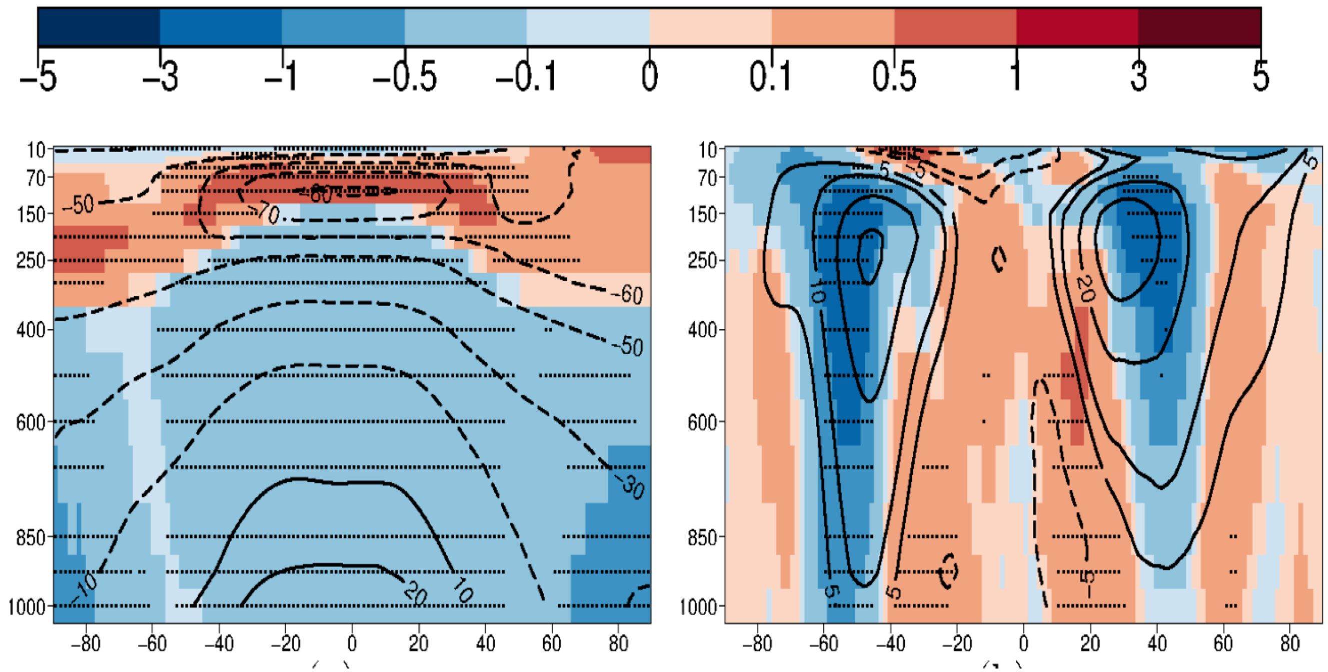


Temperature (°C) Zonal wind ($m.s^{-1}$)

Climatology (contours) and anomalies (shading), Ménégoz et al. (2017)

Volcanic signal

Second winter anomalies after a Pinatubo eruption, cold AMV case

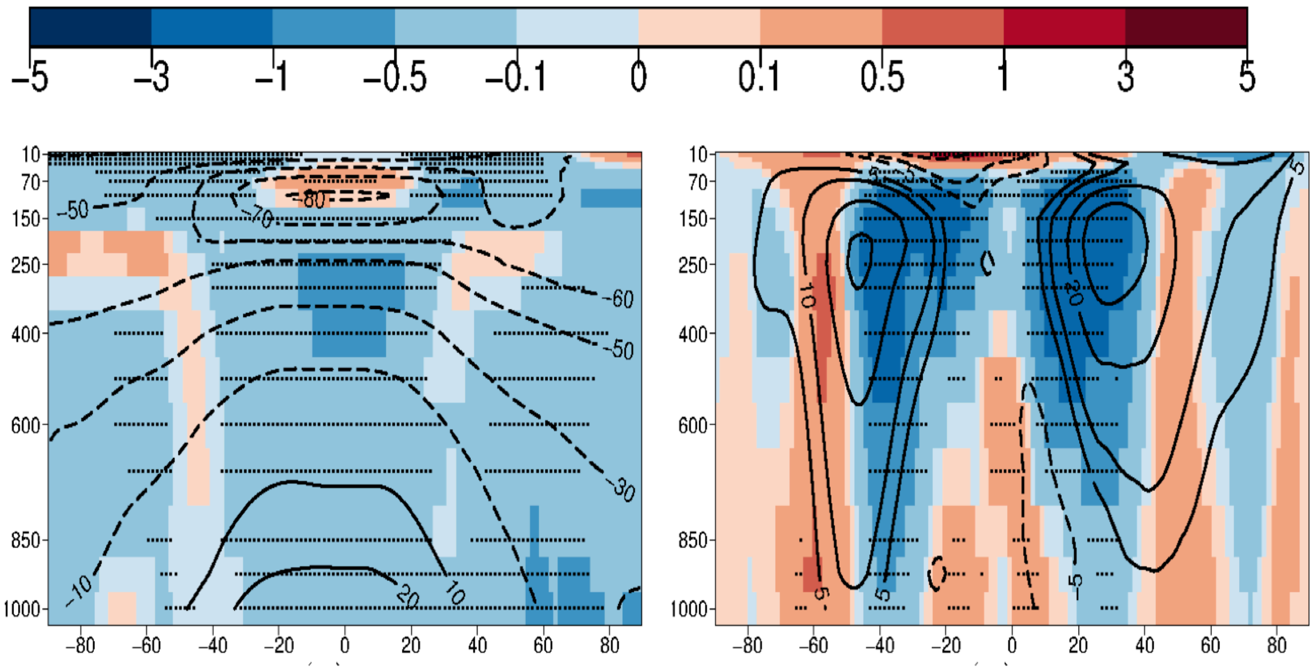


Temperature (°C) Zonal wind ($m.s^{-1}$)

Climatology (contours) and anomalies (shading), Ménégoz et al. (2017)

Volcanic signal

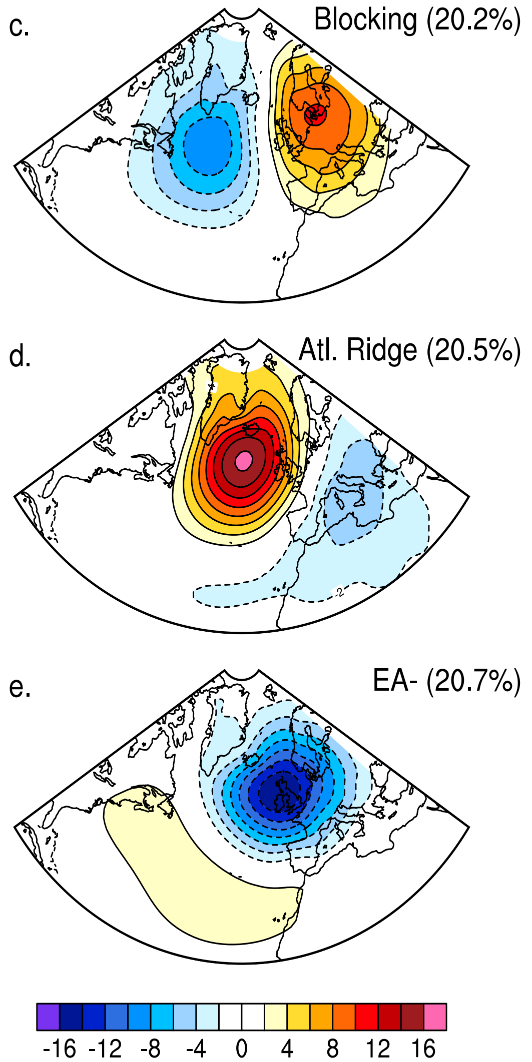
Third winter anomalies after a Pinatubo eruption, cold AMV case

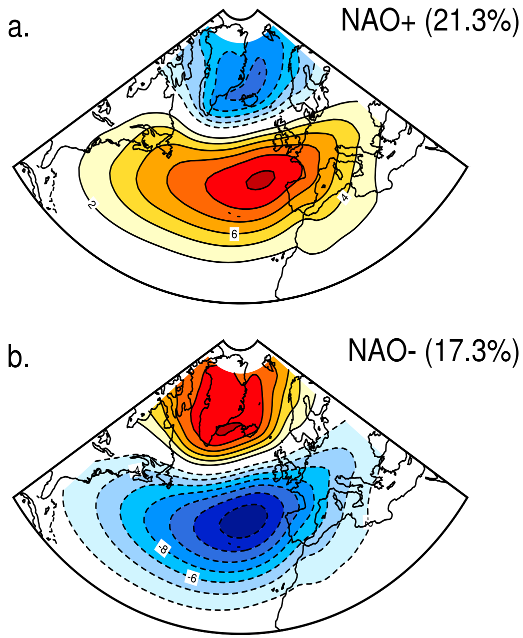


Temperature (°C)   Zonal wind ($m.s^{-1}$)

Climatology (contours) and anomalies (shading), Ménégoz et al. (2017)

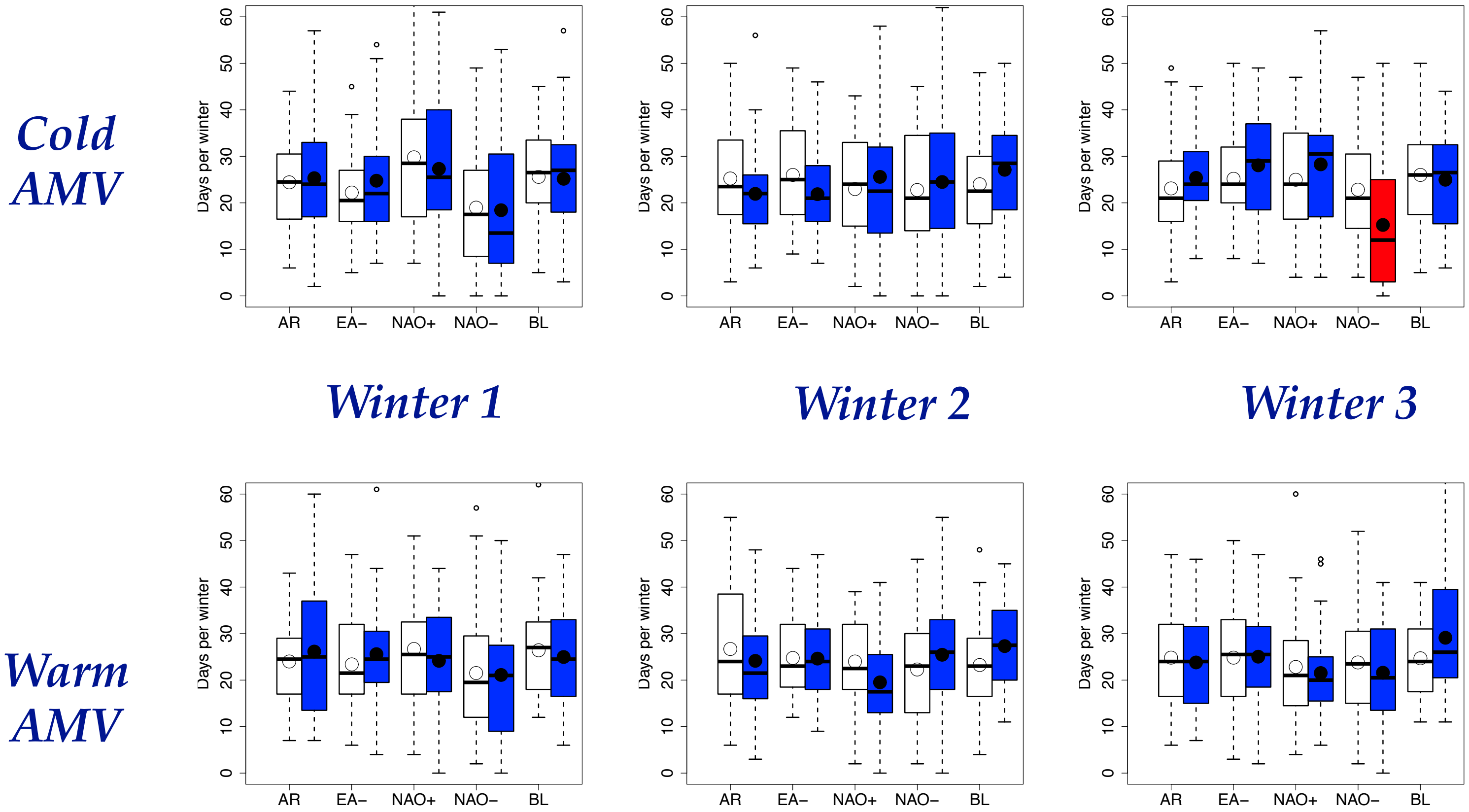
Weather regimes





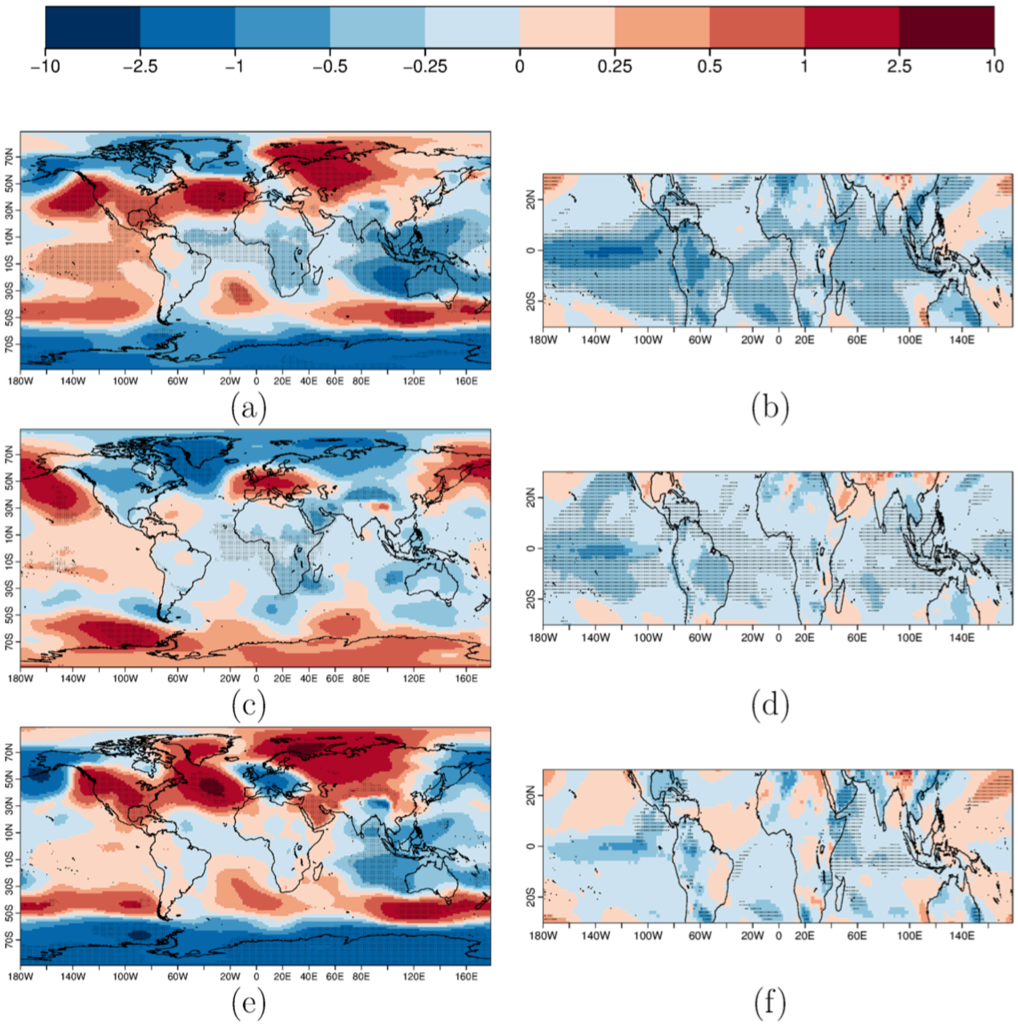
Centroids of the five wintertime North Atlantic weather regimes obtained from daily anomalous mean sea level pressure maps (piControl, 850 Yrs)

Weather regimes changes



Weather regime occurrences simulated during the winters after eruptions simulated under cold (up) and warm (bottom) AMV conditions.

Cold tropics under cold AMV



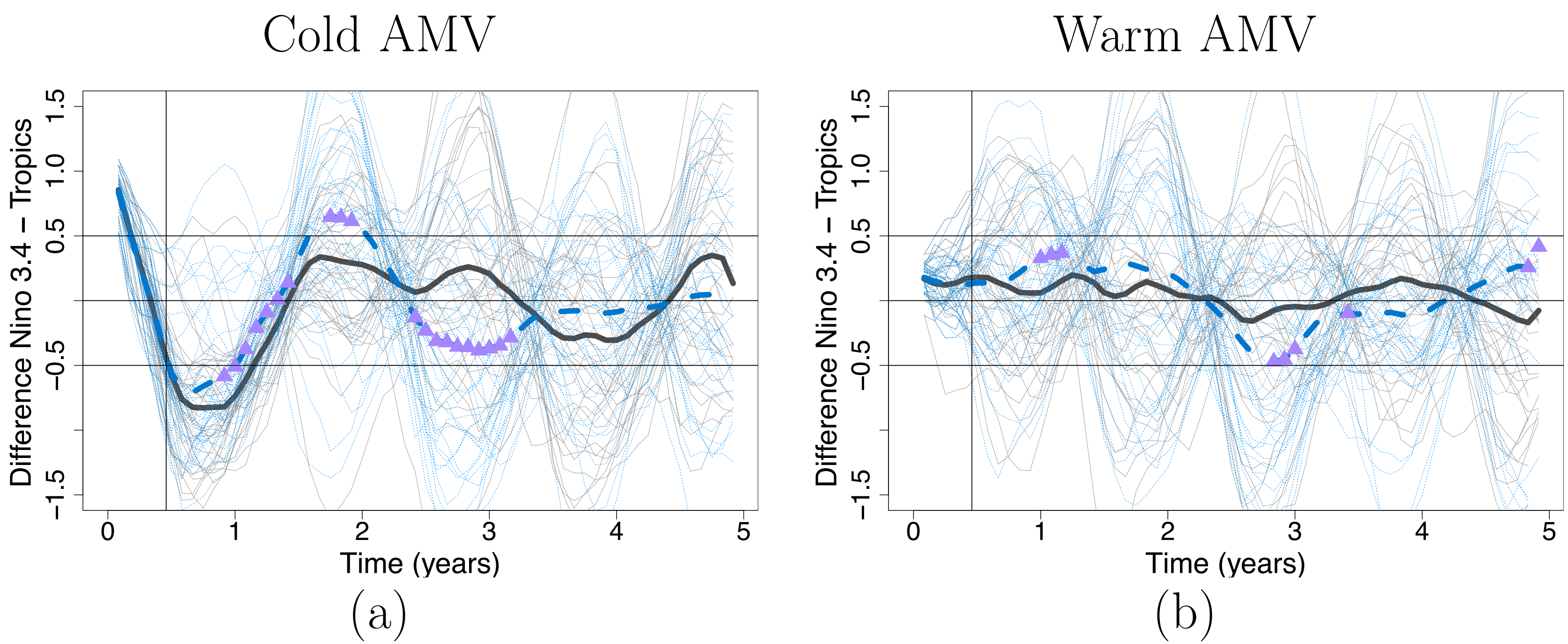
Cold AMV

Warm AMV

Cold – warm AMV

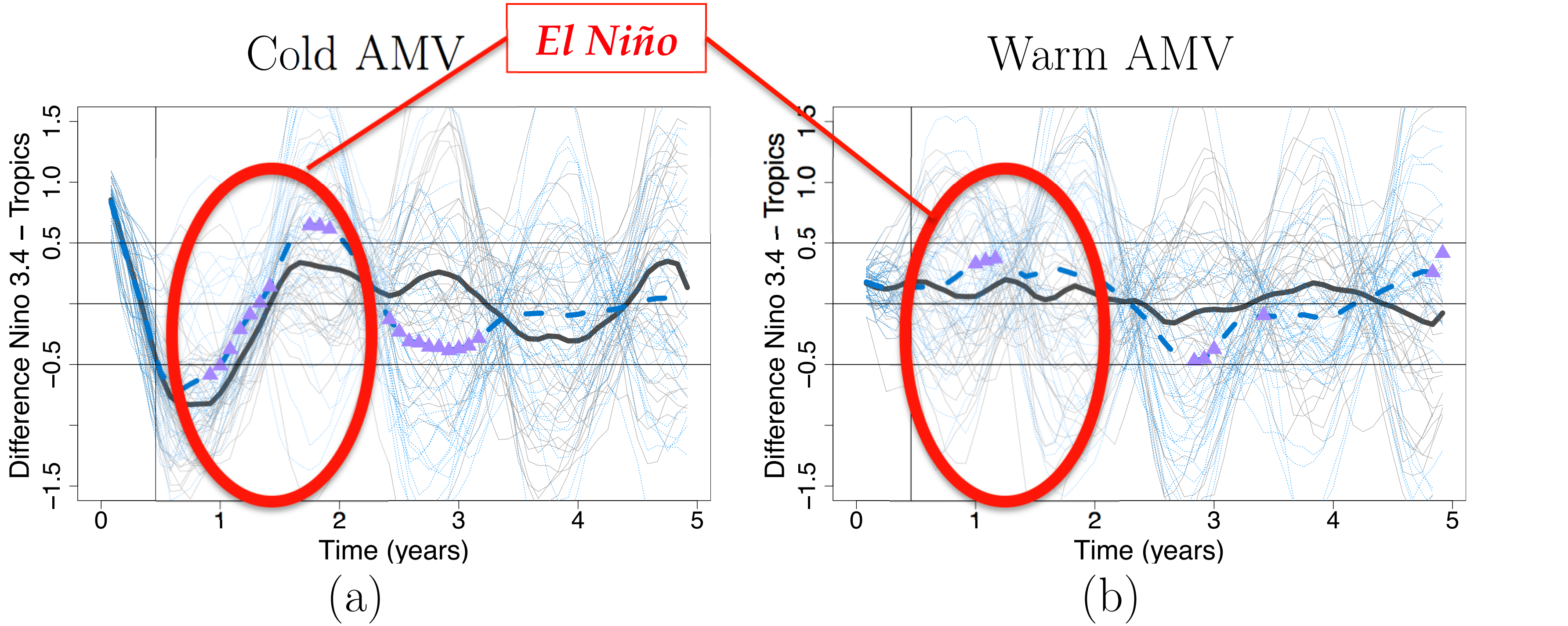
SLP anomaly *T° anomaly* *(3rd winter after the eruption)*

El Niño – La Niña events after volcanic eruptions



Relative SST anomaly over the Niño 3.4 region with respect to the tropical ocean belt (20°S-20°N), in the control (black) and the Pinatubo (blue) experiments. Purple triangles appear for the significance of the difference between experiments. Fom Ménégoz et al. (2017), inspired from Khodri et al. (2017).

El Niño – La Niña events after volcanic eruptions



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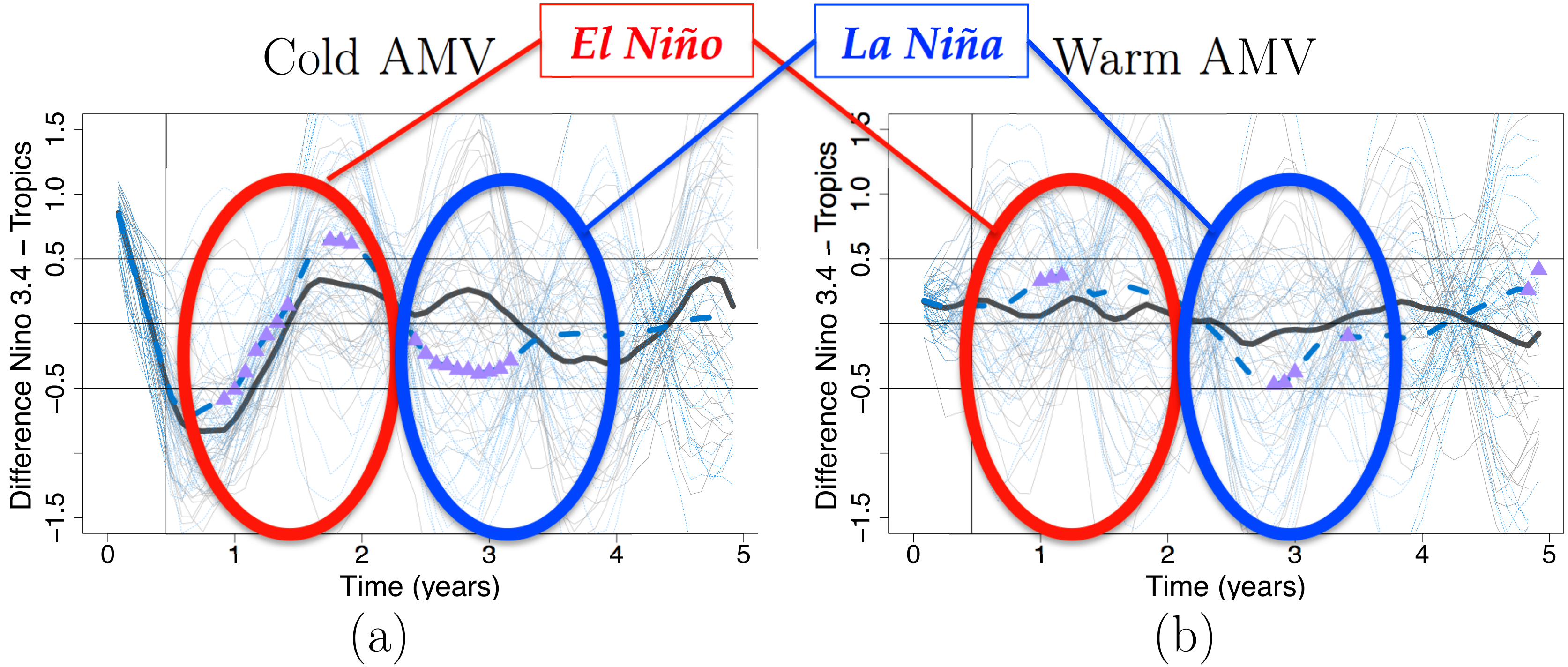

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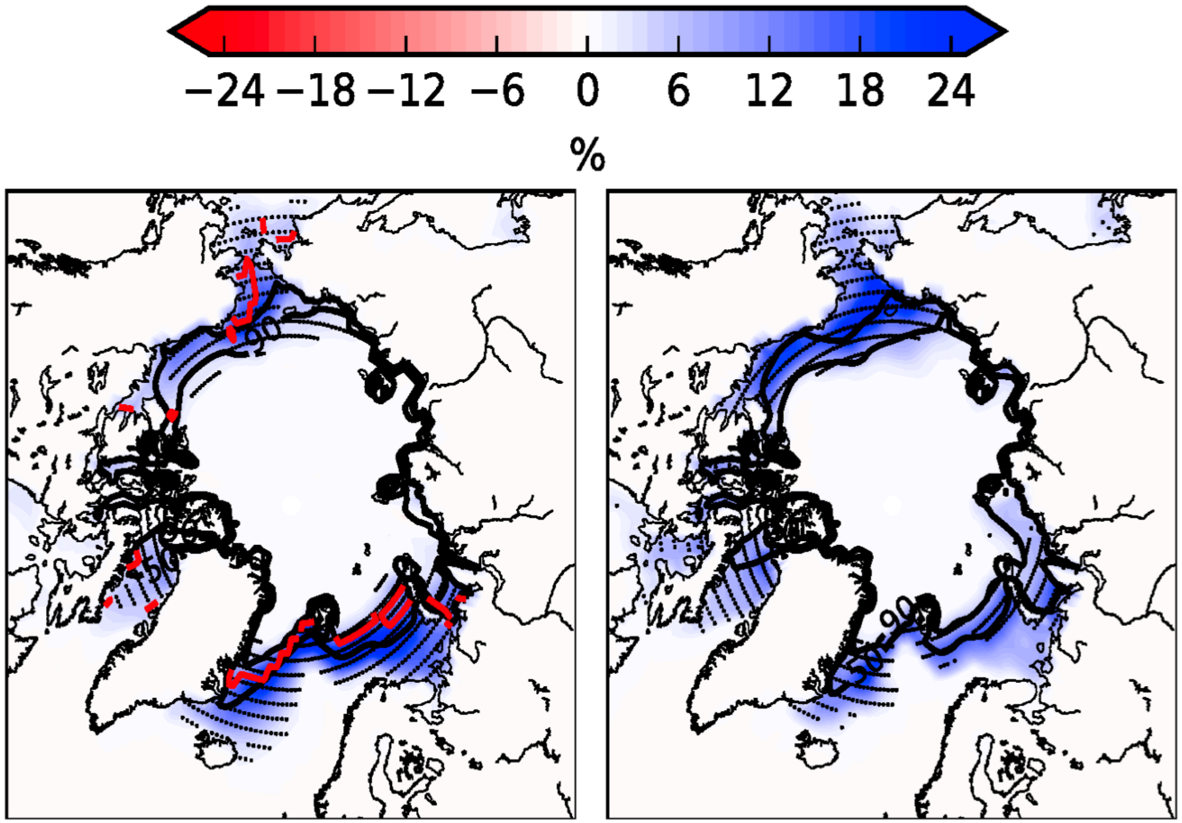
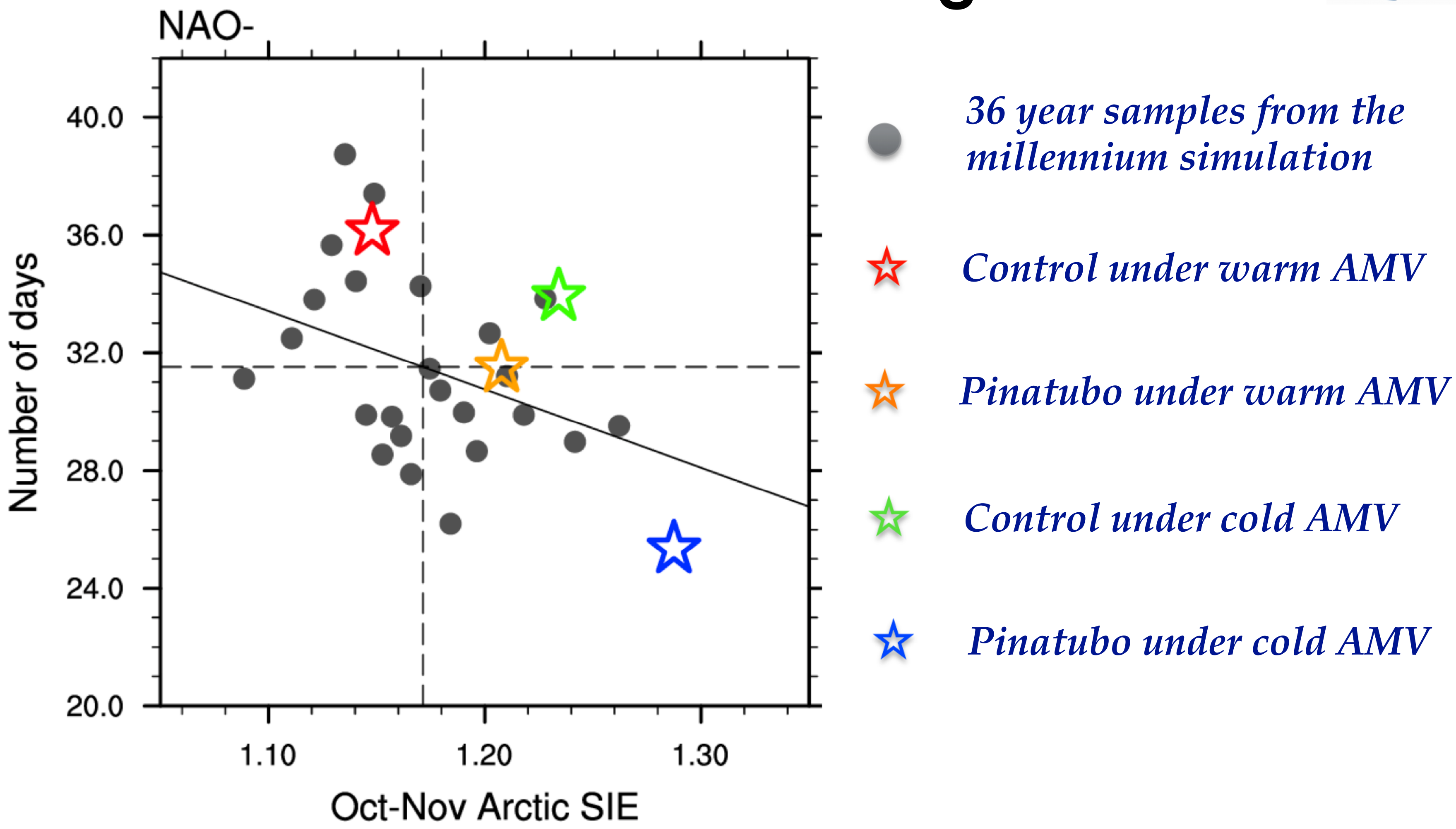
Sea-ice anomalies



Cold AMV *Warm AMV*

Sea-ice anomalies simulated the third autumn after a Pinatubo eruption. South of the red line, the response is stronger in the case of the cold AMV situation

Autumn sea-ice versus winter NAO- regime

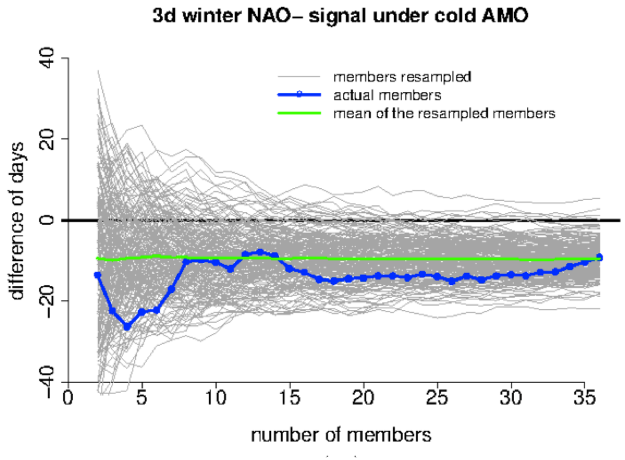


NAO- change the third winter

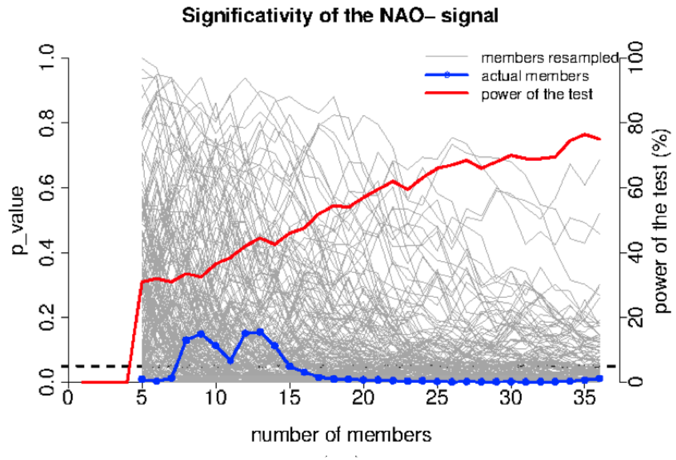
Cold AMO

Actual members

Members resampled



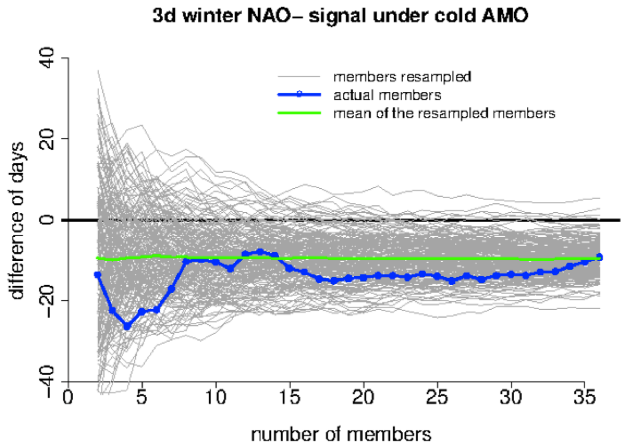
Volcanic signal / member mean (days)

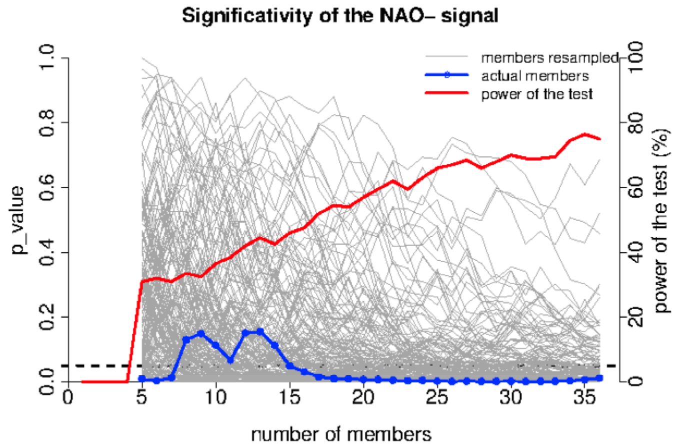


P-value / power

NAO- change the third winter

Cold AMO





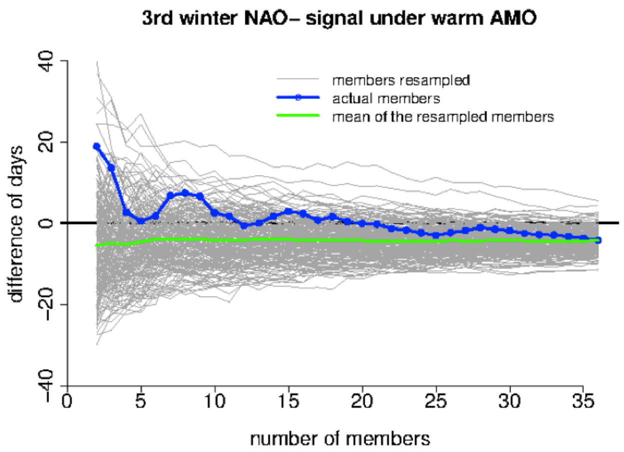
Actual members

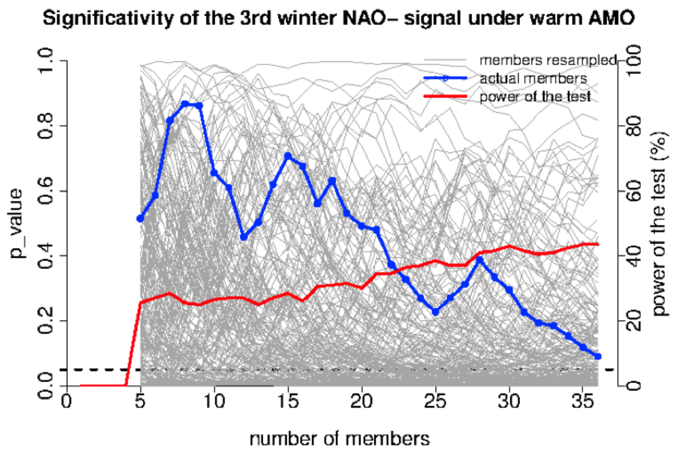
Members resampled

Volcanic signal / member mean (days)

P-value / power

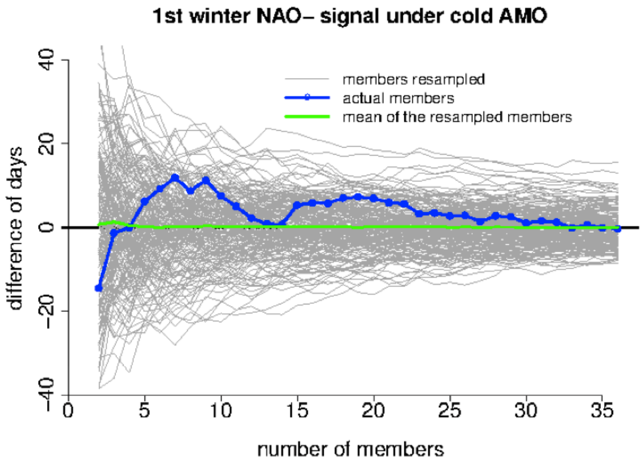
Warm AMO

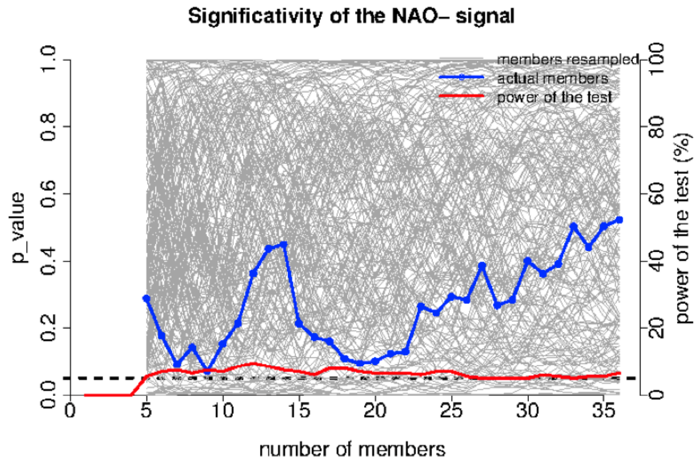




NAO- change the first winter

Cold AMO





Actual members

Members resampled

Volcanic signal / member mean (days)

P-value / power

Do volcanic eruptions affect the NAO?

→ Probably during several winters after eruptions larger than the Pinatubo

→ The third winter after a Pinatubo eruption in the CNRM-CM5 model, with a small signal-noise ratio. Small ensemble experiments => misleading results!

- Ménégoz, M., Cassou, C., Swingedouw, D., Bretonnière, P.-A., Doblas-Reyes, F., 2017, Modulation of the climate response to a volcanic eruption by the Atlantic Multidecadal Variability, Climate Dynamics, https://doi.org/10.1007/s00382-017-3986-1
- Swingedouw, D., Mignot, J., Ortega, P., Khodri, M., Ménégoz, M., Cassou, C., Hanquiez, V., 2017, Impact of explosive volcanic eruptions on the main climate variability modes, Global and Planetary Change, Vol. 150, P. 24–45.
- Khodri, M., Izumo, T., Vialard, J., Janicot, S., Cassou, C., Lengaigne, M., ... & Robock, A. (2017). Tropical explosive volcanic eruptions can trigger El Niño by cooling tropical Africa. Nature Communications, 8(1), 778.

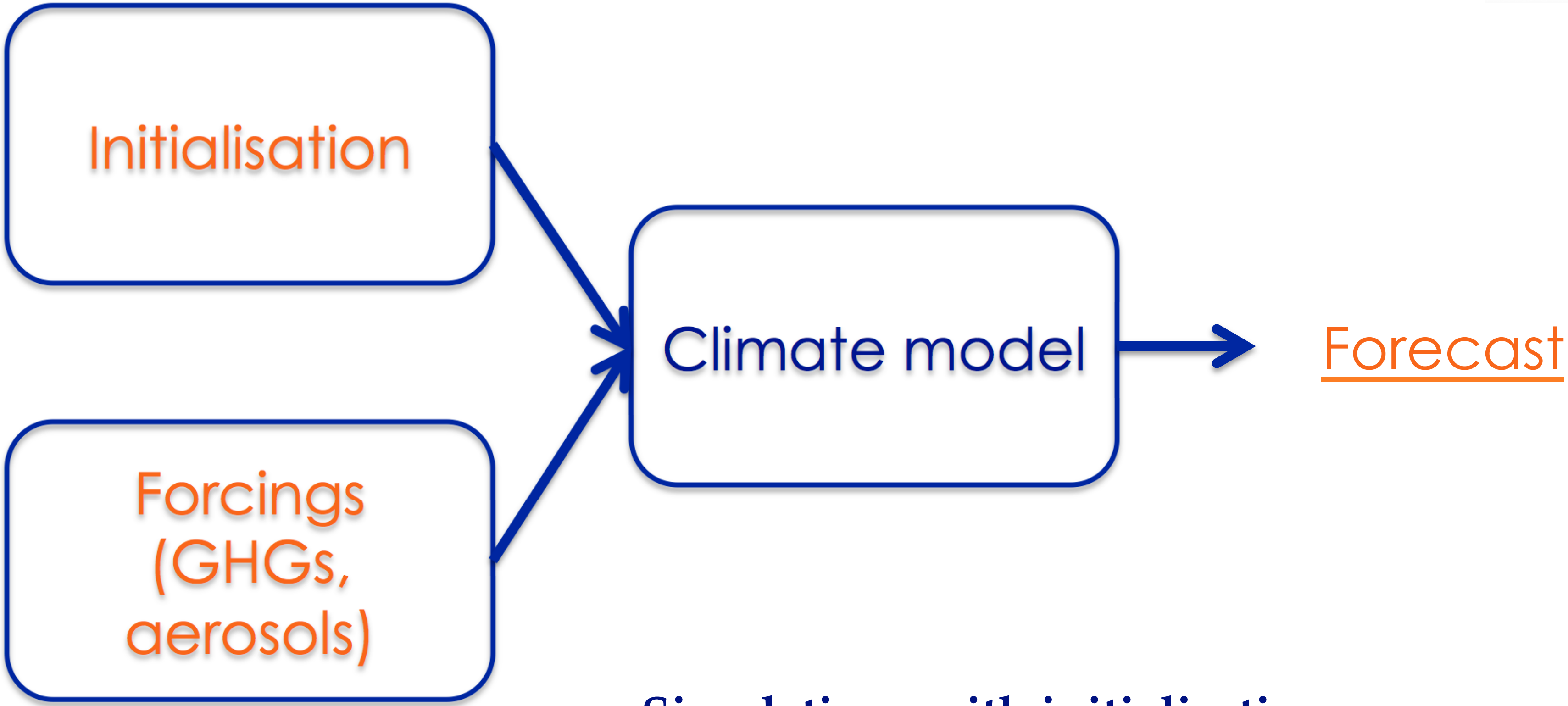
→ Introduction

→ Do volcanic eruptions affect the NAO?

→ **Can we forecast the climate response to volcanic eruptions?**


Agung (1963)
El Chichón (1982)
Pinatubo (1991)
Sarychev volcano, 2009, NASA

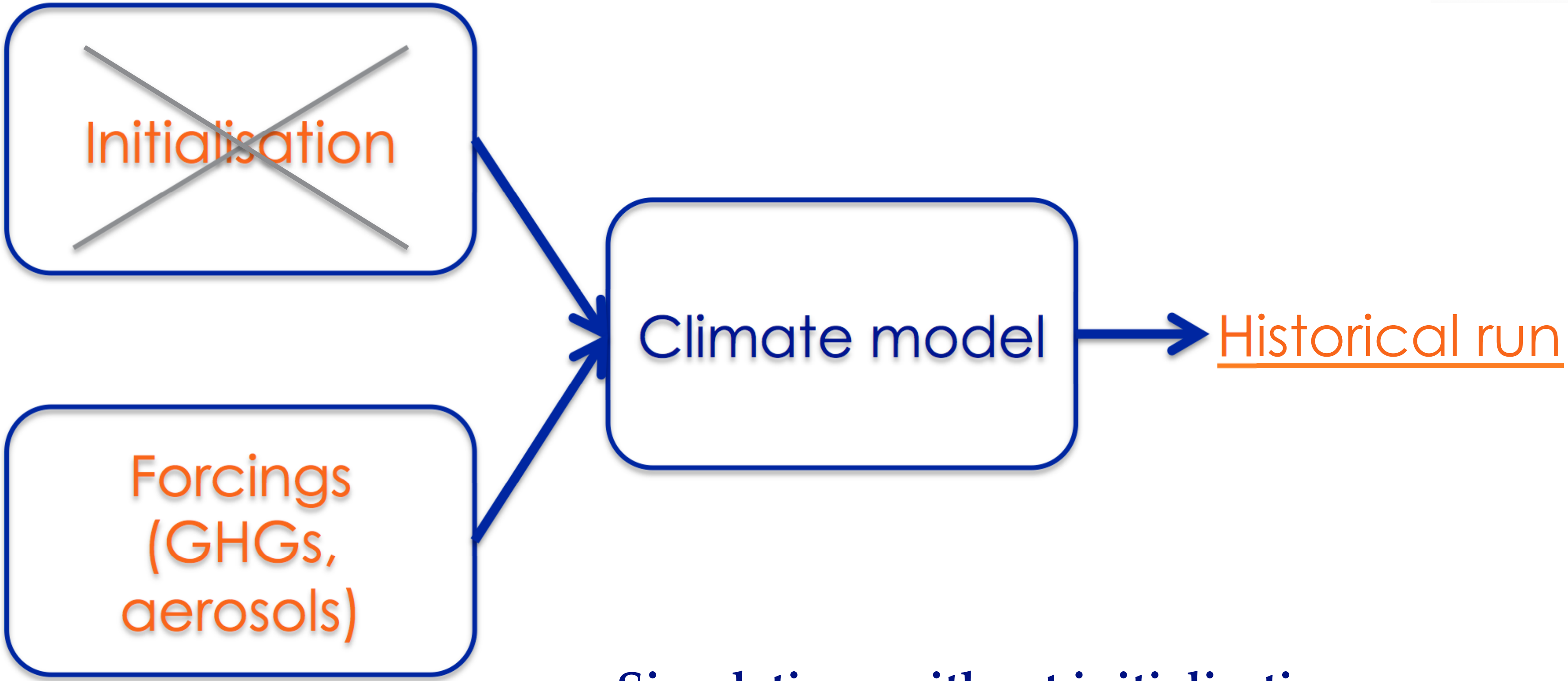
Forecasts



→ **Simulations with initialisation**

→ **Simulations with estimation of future forcing**

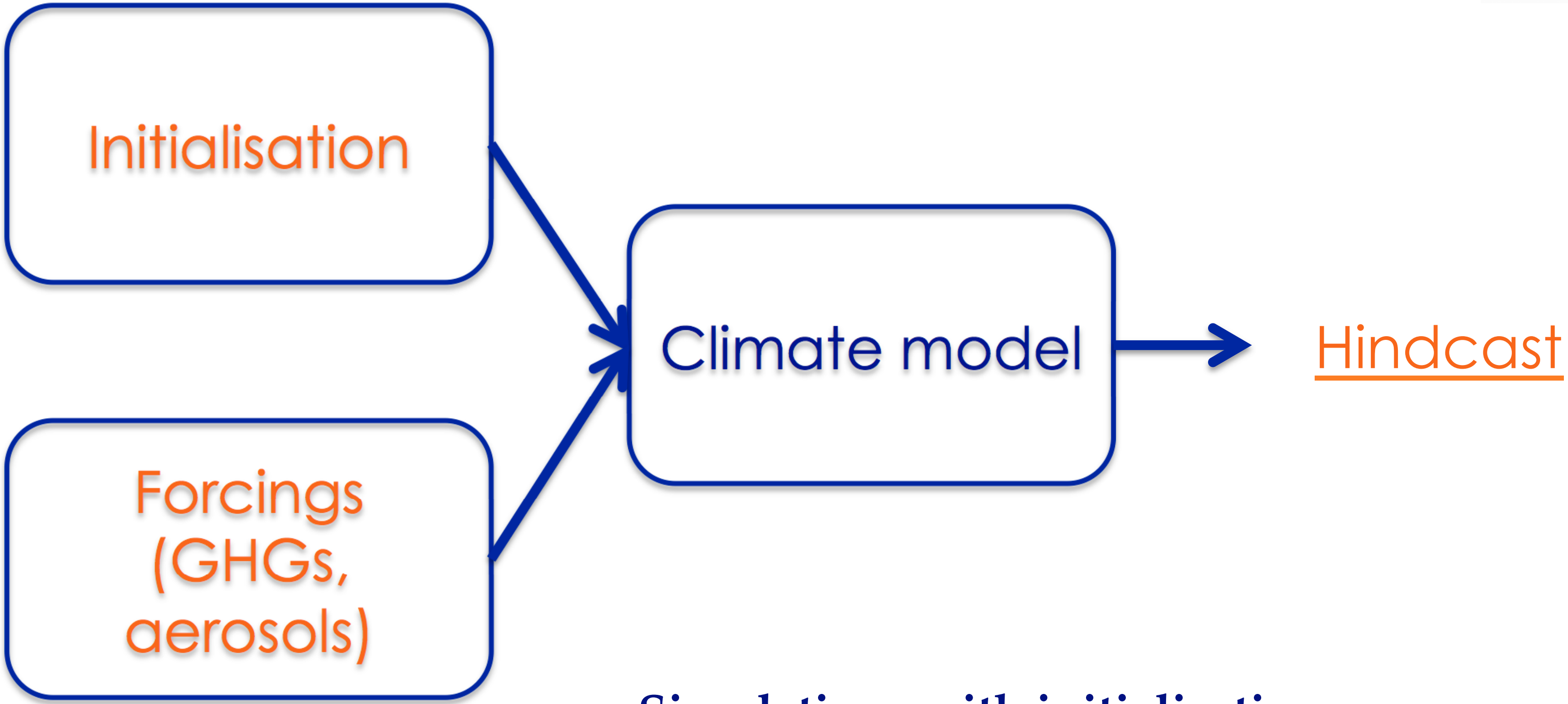
Forecasts



→ **Simulations without initialisation**

→ **Simulations with observed forcing**

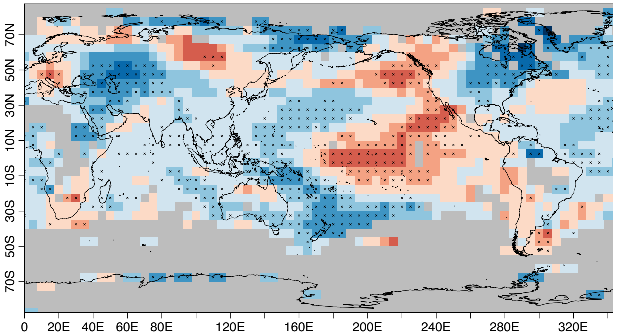
Forecasts



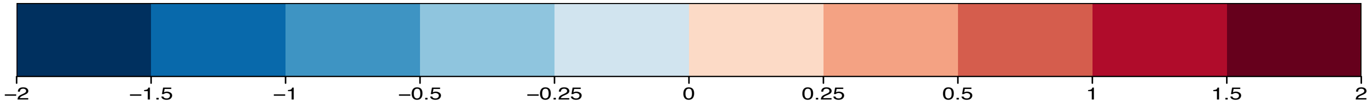
→ **Simulations with initialisation**

→ **Simulations with observed forcing**

Pinatubo

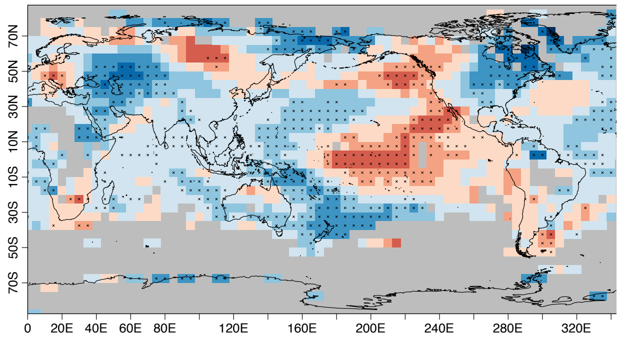


Observation

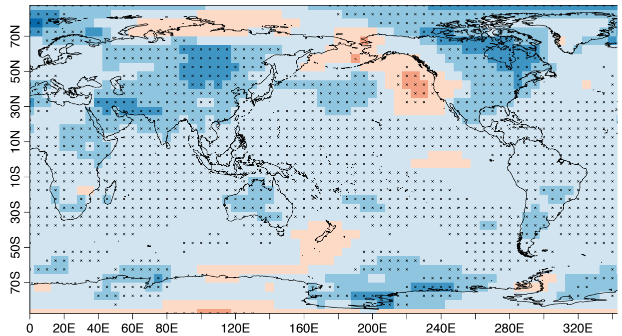


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

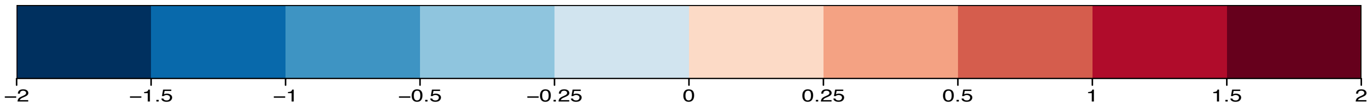
Pinatubo



Observation



No initialisation



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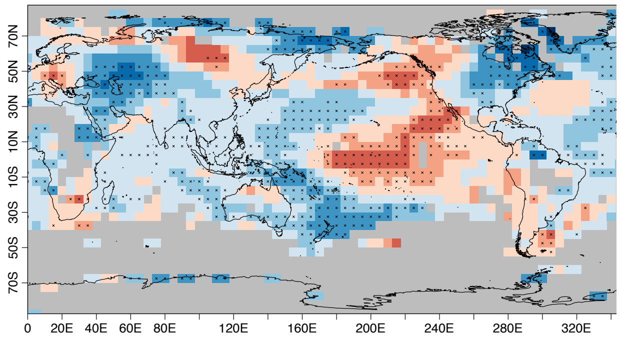
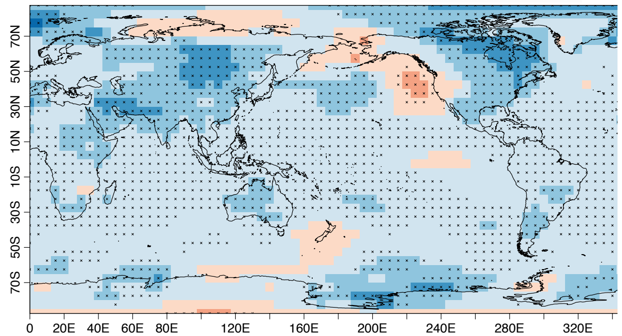
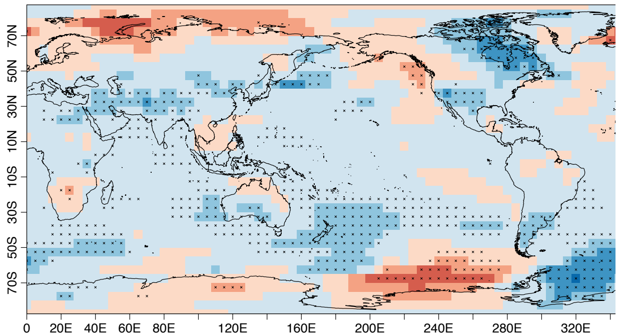


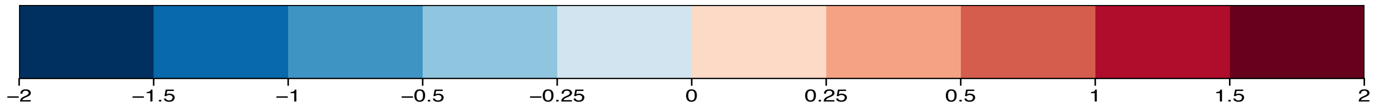
Observation



No initialisation

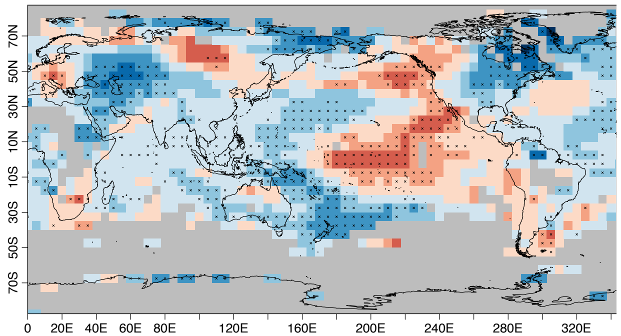


Initialisation, volcanic forcing

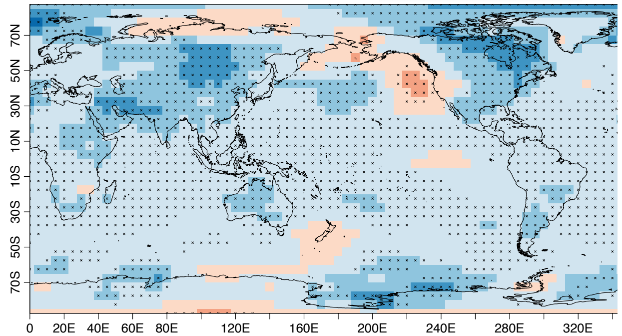


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

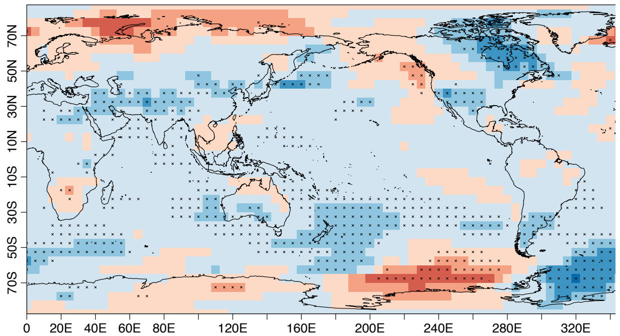
Pinatubo



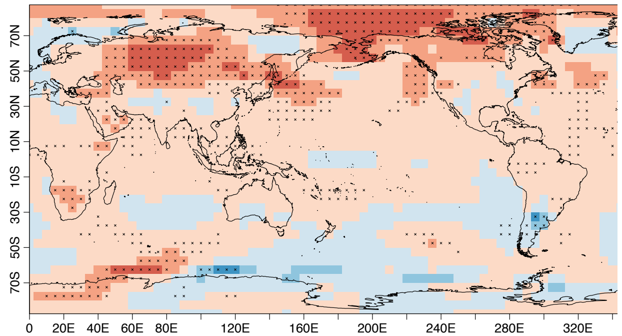
Observation



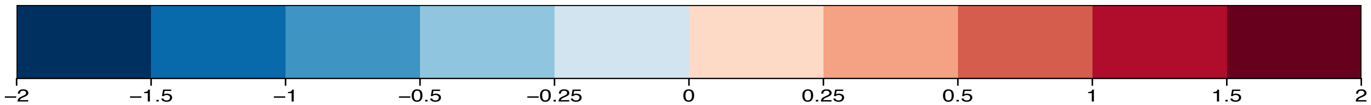
No initialisation



Initialisation, volcanic forcing

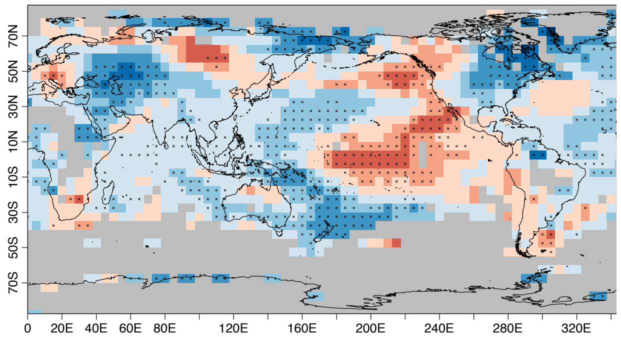


No volcanic forcing

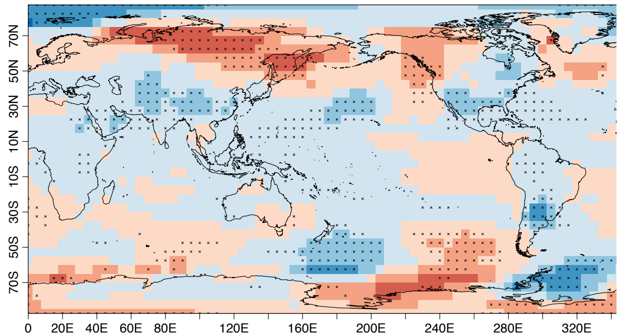


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

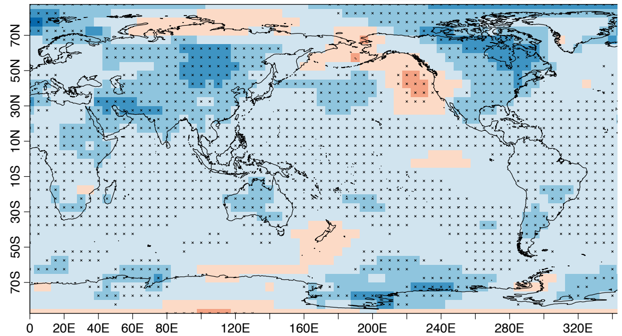
Pinatubo



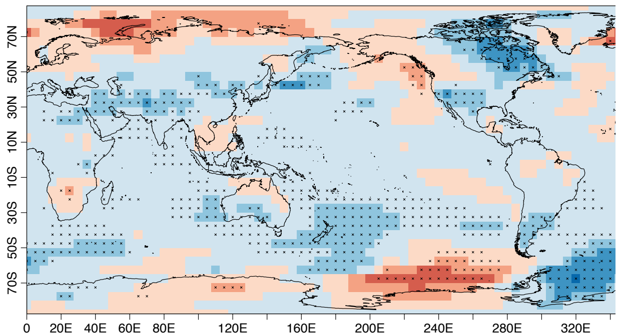
Observation



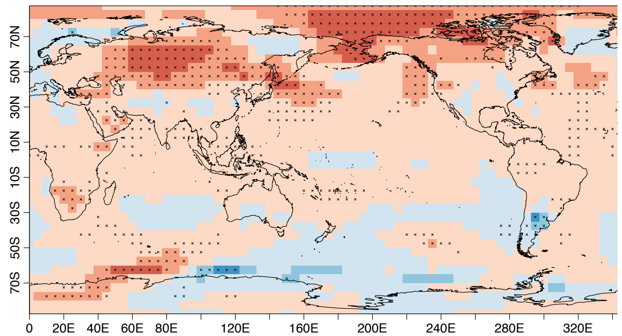
Using El Chichon forcing



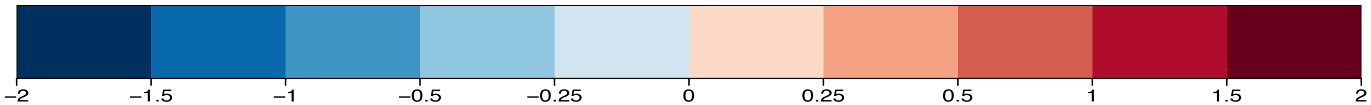
No initialisation



Initialisation, volcanic forcing

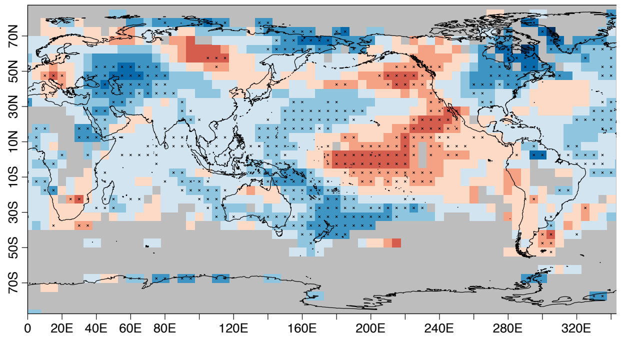


No volcanic forcing

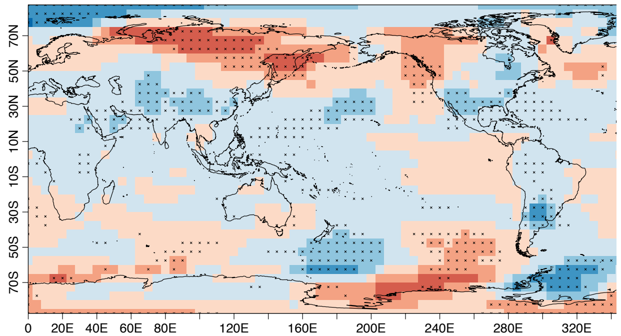


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

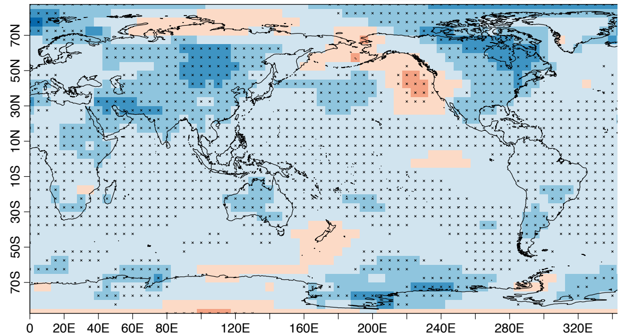
Pinatubo



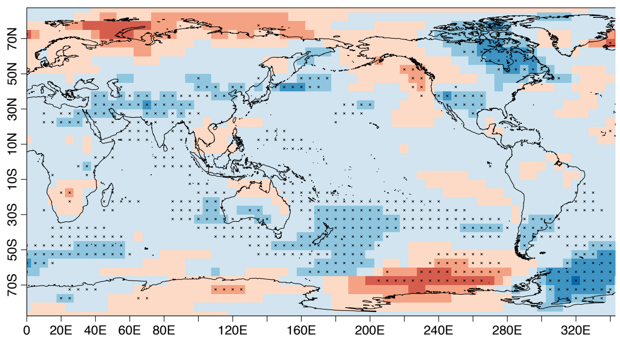
Observation



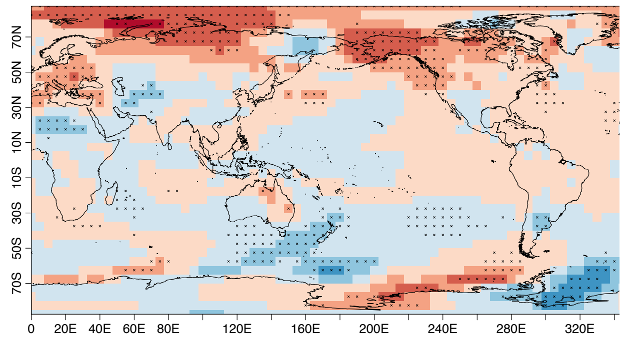
Using El Chichon forcing



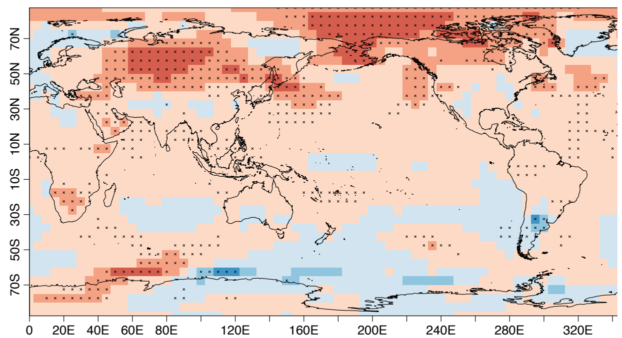
No initialisation



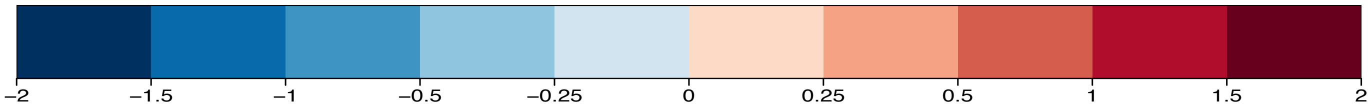
Initialisation, volcanic forcing



Idealized volcanic forcing

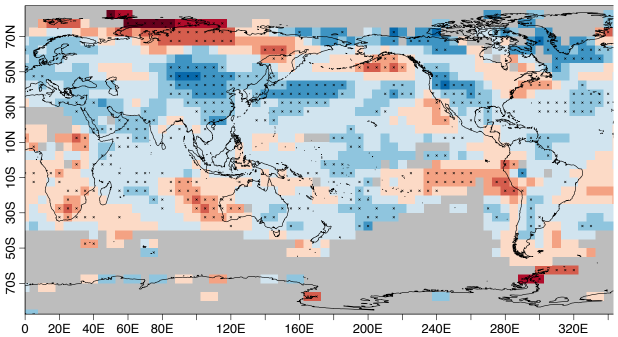


No volcanic forcing

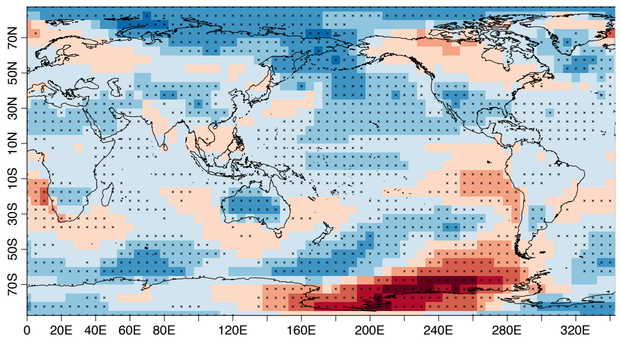


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

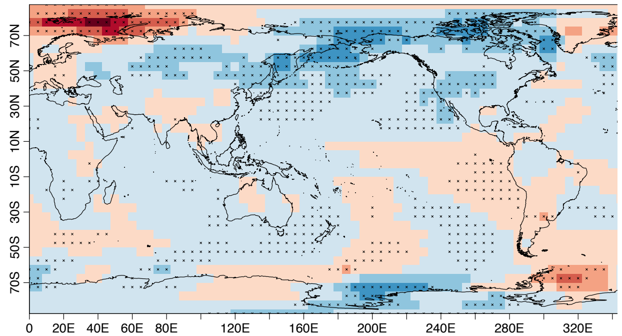
El Chichón



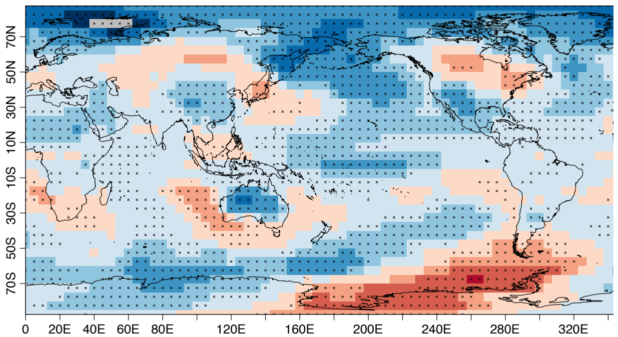
Observation



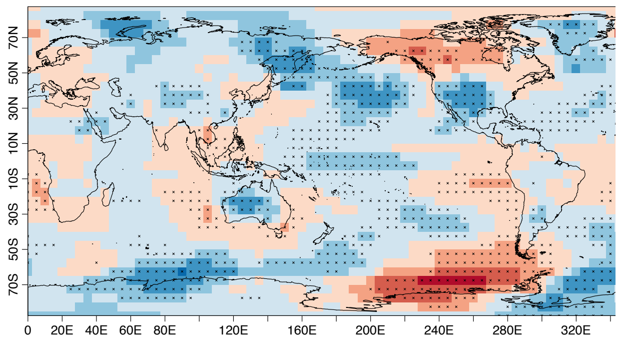
Using Agung forcing



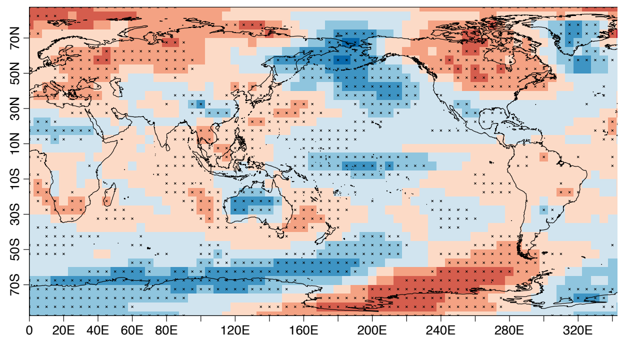
No initialisation



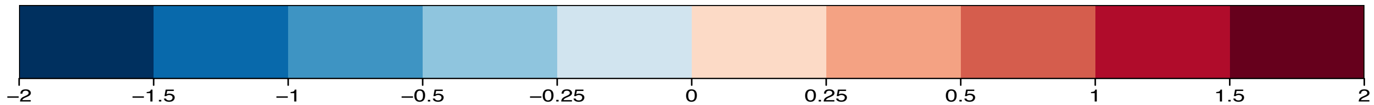
Initialisation, volcanic forcing



Idealized volcanic forcing

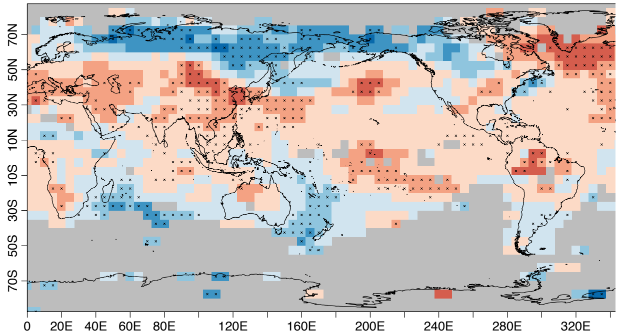


No volcanic forcing

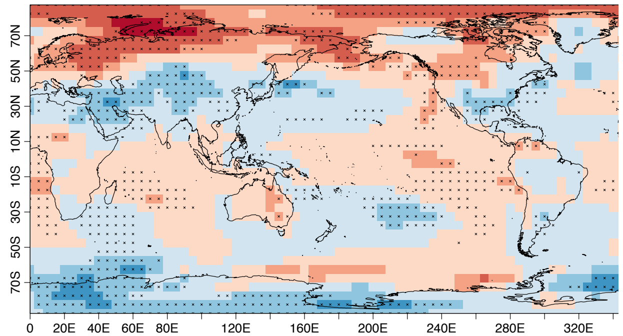


Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

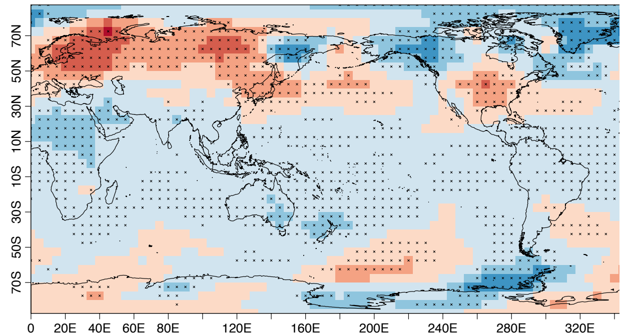
Agung



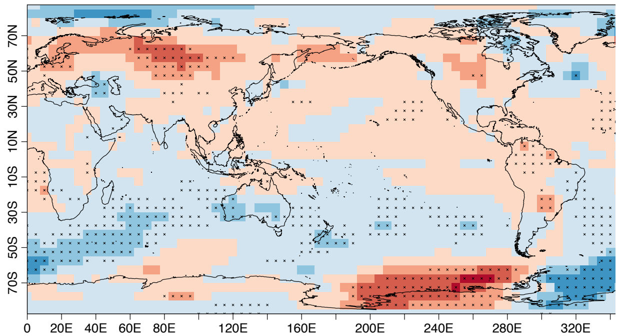
Observation



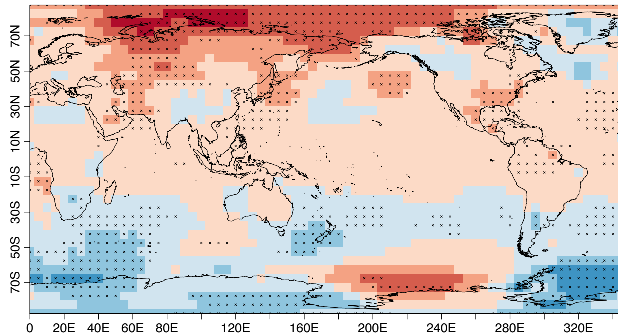
Using El Chichon forcing



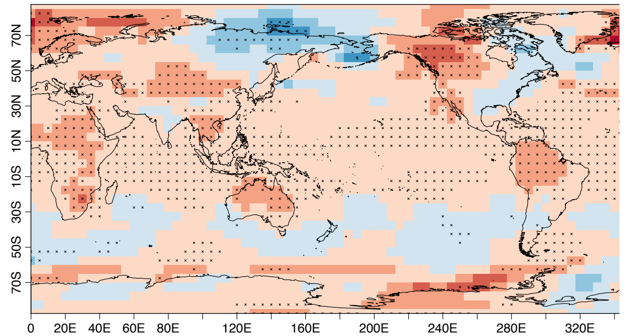
No initialisation



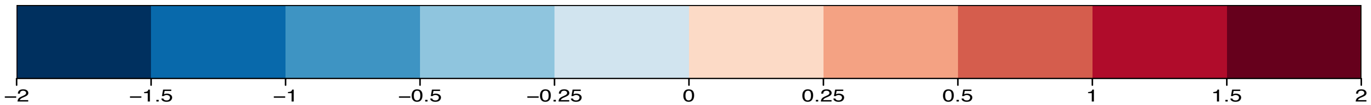
Initialisation, volcanic forcing



Idealized volcanic forcing

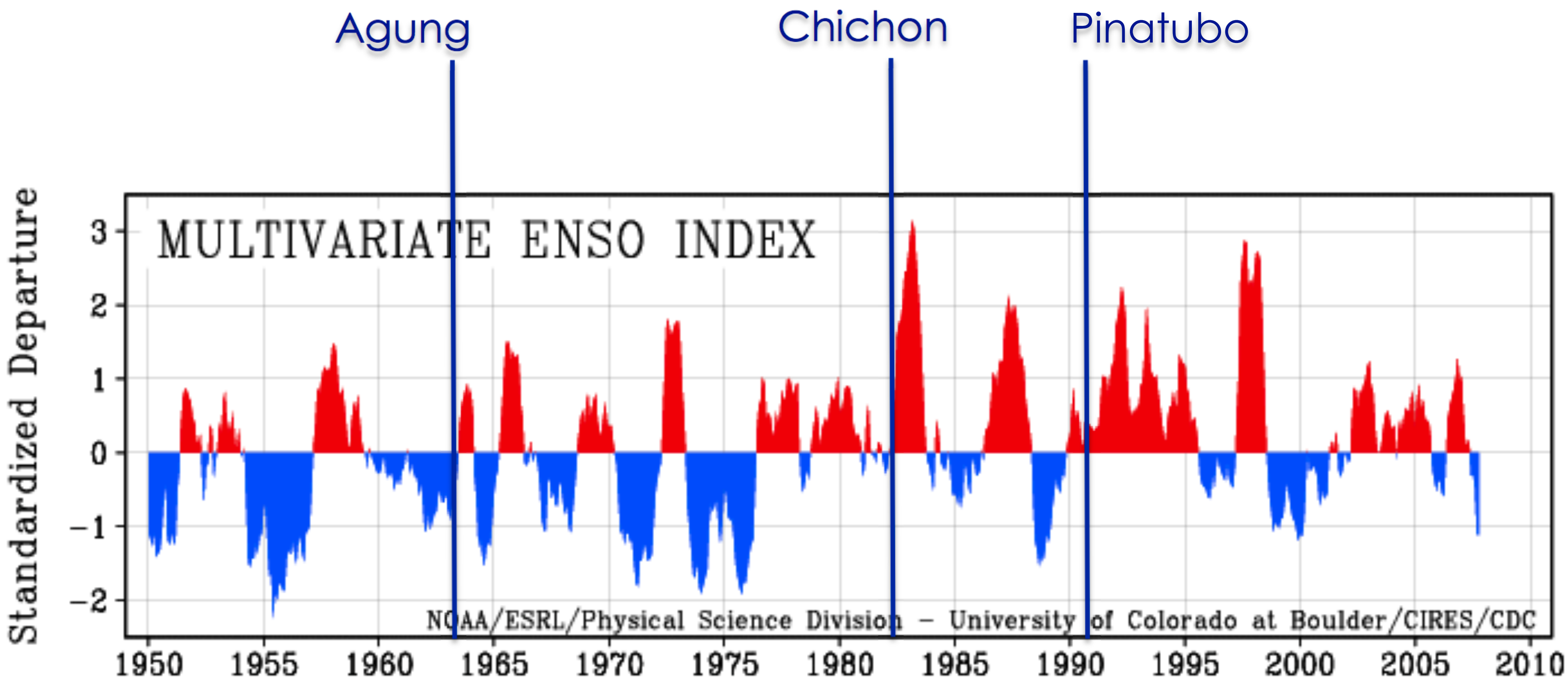


No volcanic forcing



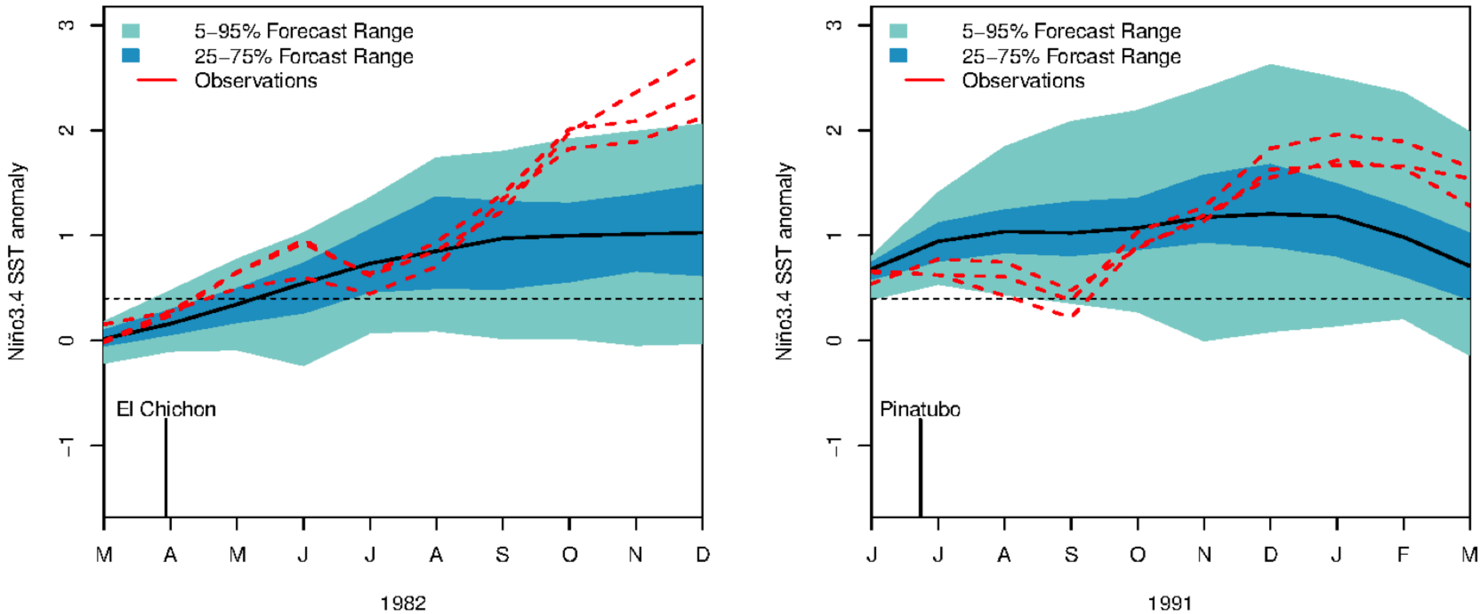
Surface temperature anomalies (°C), forecast years 1-3 (EC-Earth: 5 member mean)

ENSO and volcanoes



ENSO and volcanoes

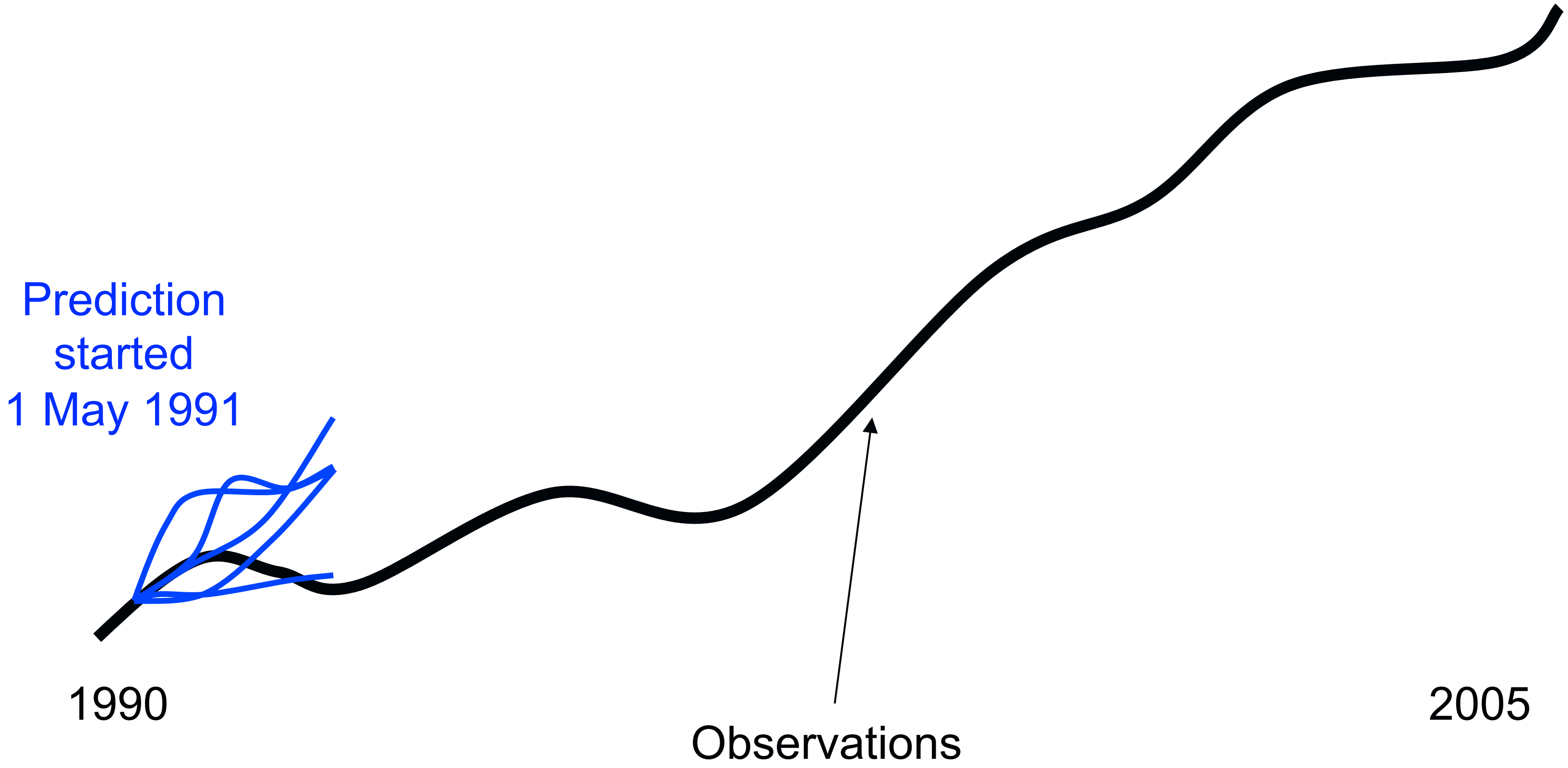
→ ECMWF forecast of Niño 3.4 SST



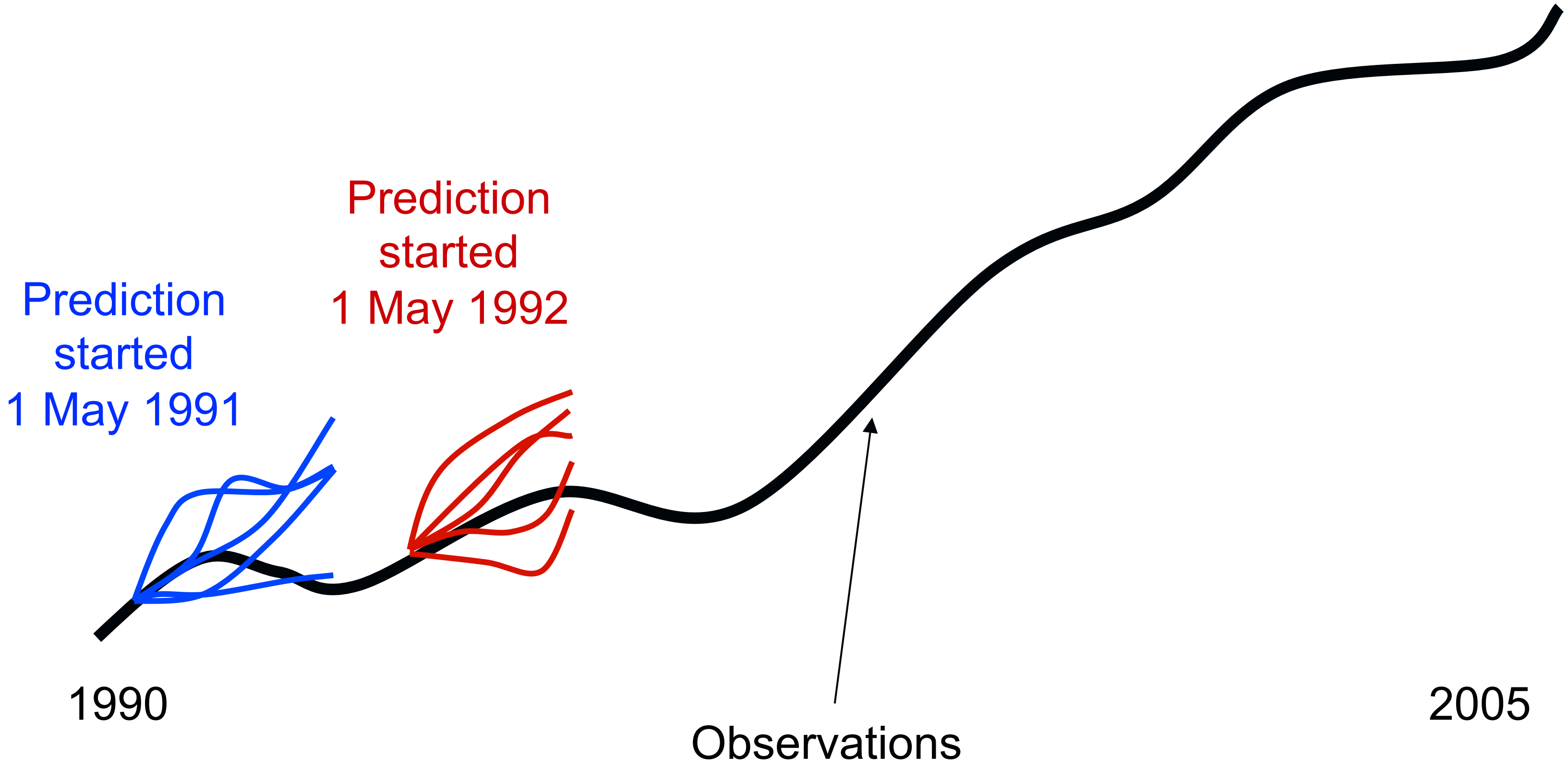
(a) ENSO prediction before El Chichon (b) ENSO prediction before Pinatubo

ECMWF S4 ensemble prediction of SST in the Niño3.4 region, simulated in real-time forecasts initialised the month before the El Chichon (a) and the Pinatubo (b) eruptions. By definition, these real-time forecasts do not include any forcing of the volcanic eruptions

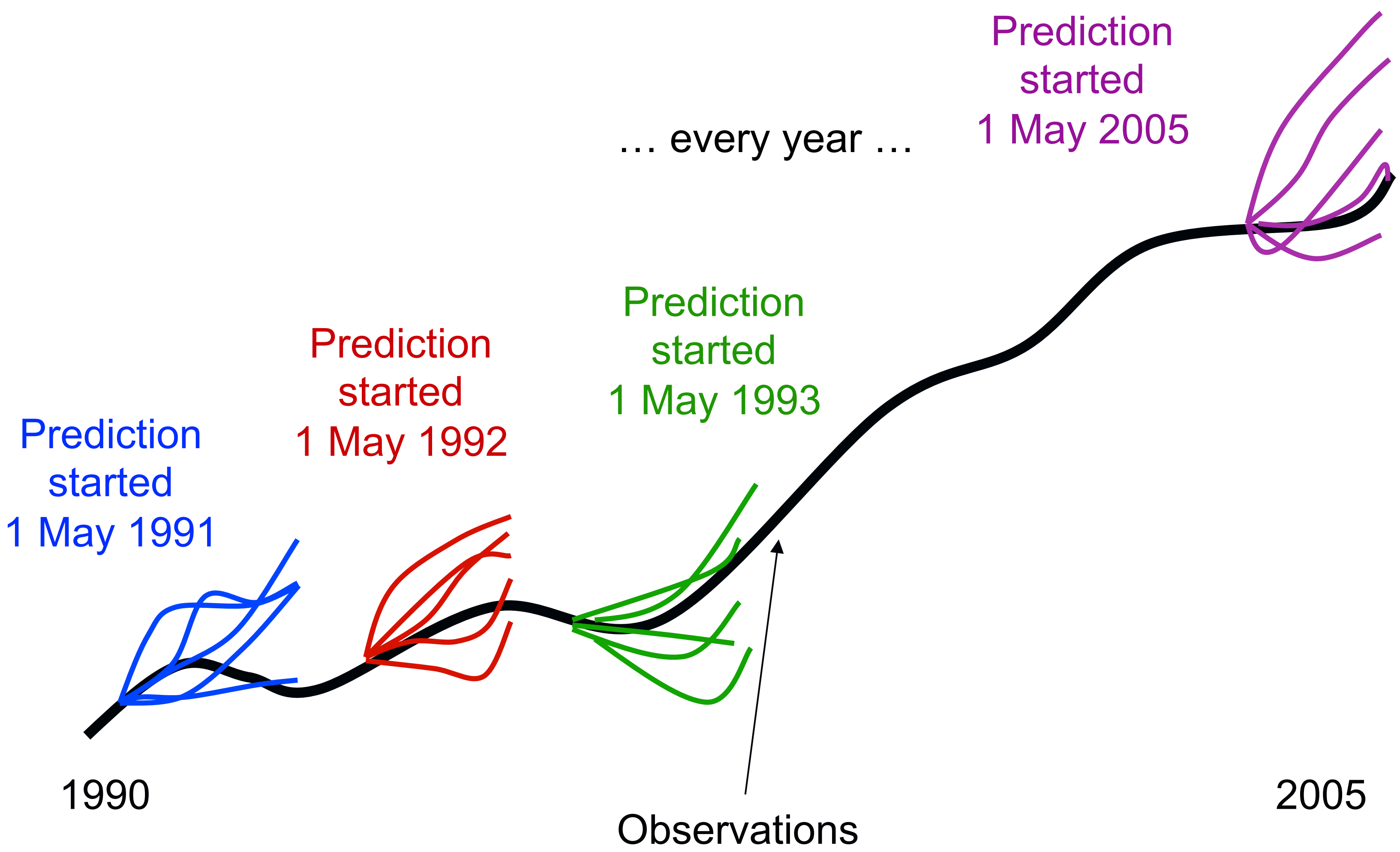
Forecast skill



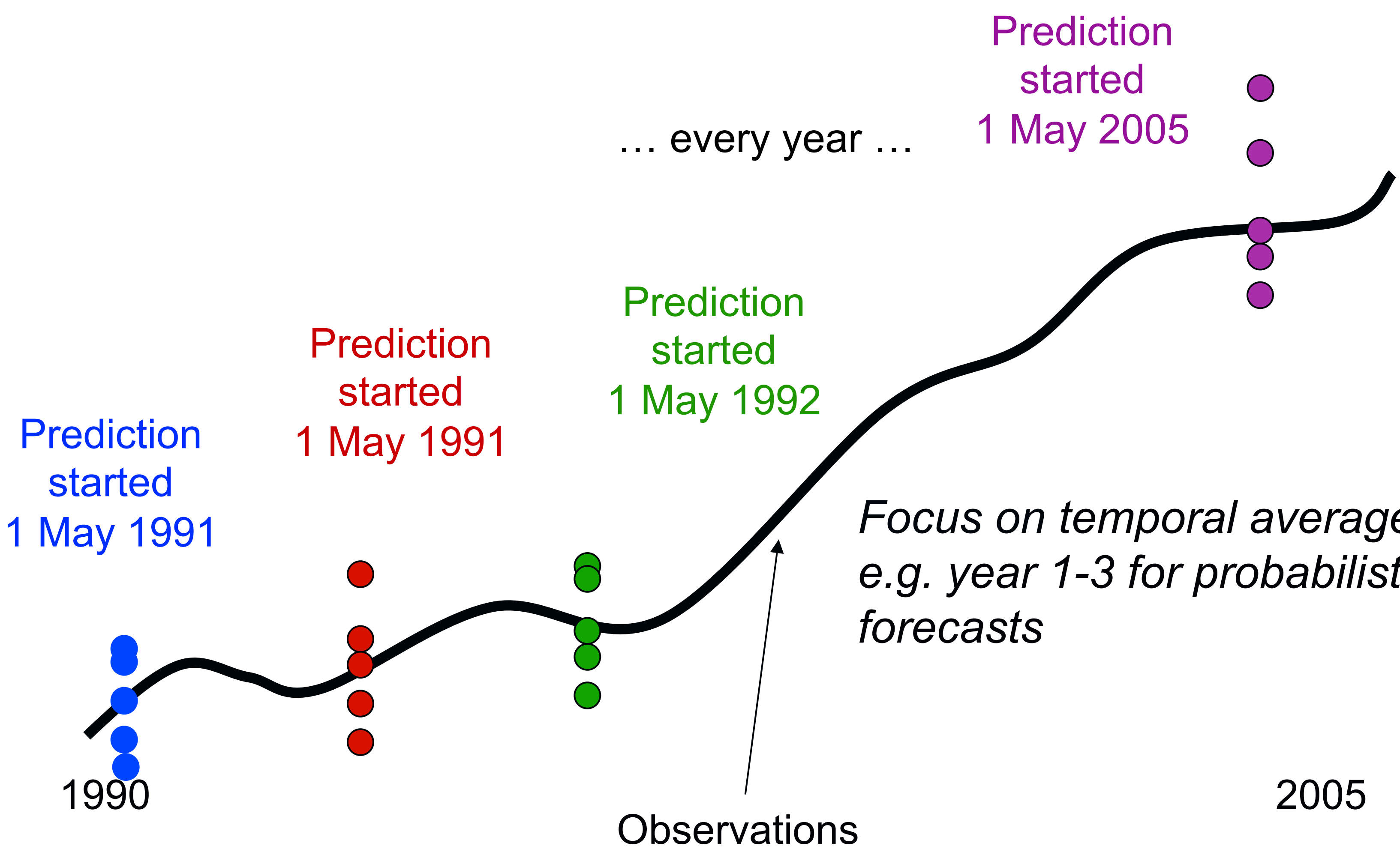
Forecast skill



Forecast skill

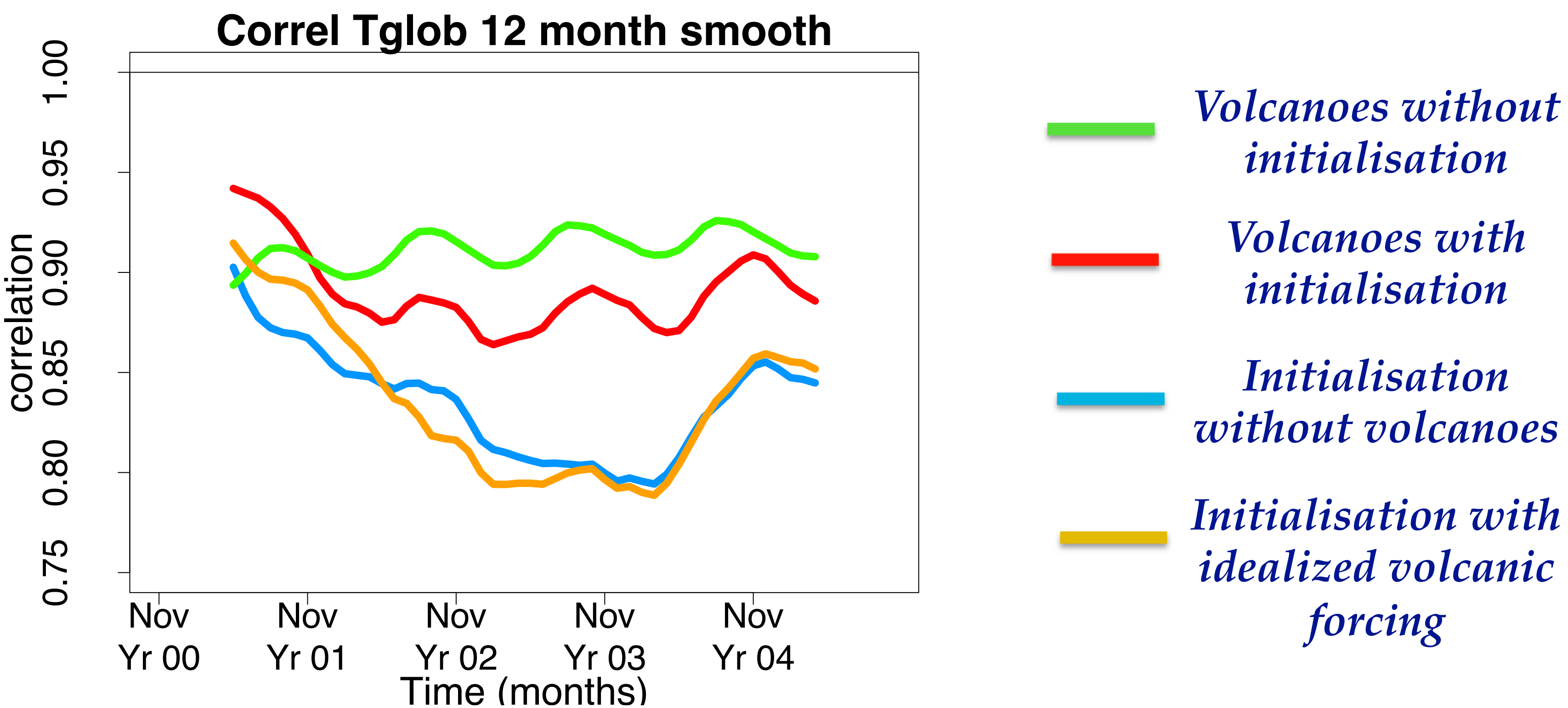


Forecast skill



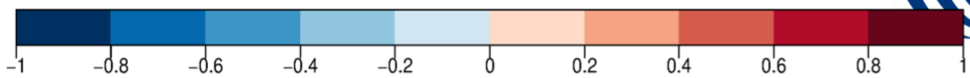
Focus on temporal averages e.g. year 1-3 for probabilistic forecasts

Correlation

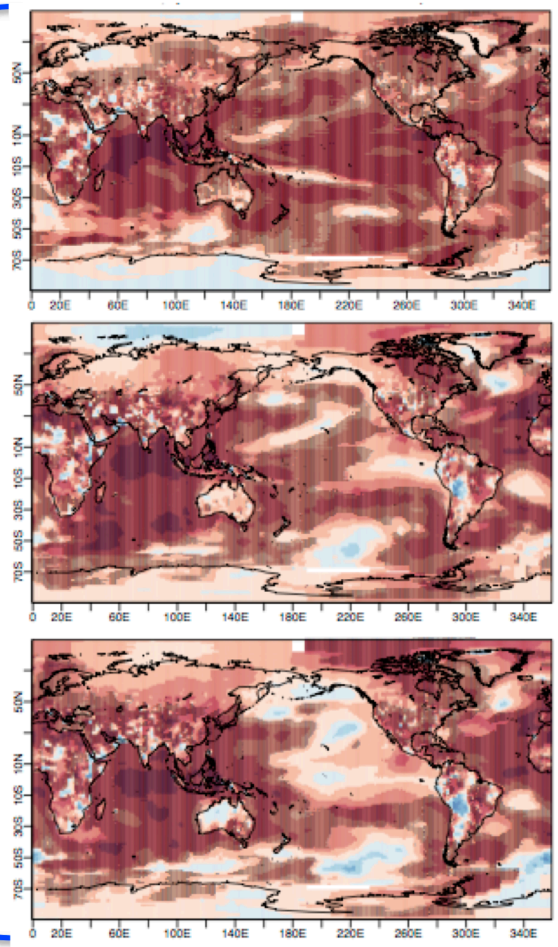


Correlation for 12 and 36 month smoothed running mean anomalies. Differences between hindcasts are not statistically significant.

Correlation



Correlation with initialisation and volcanoes

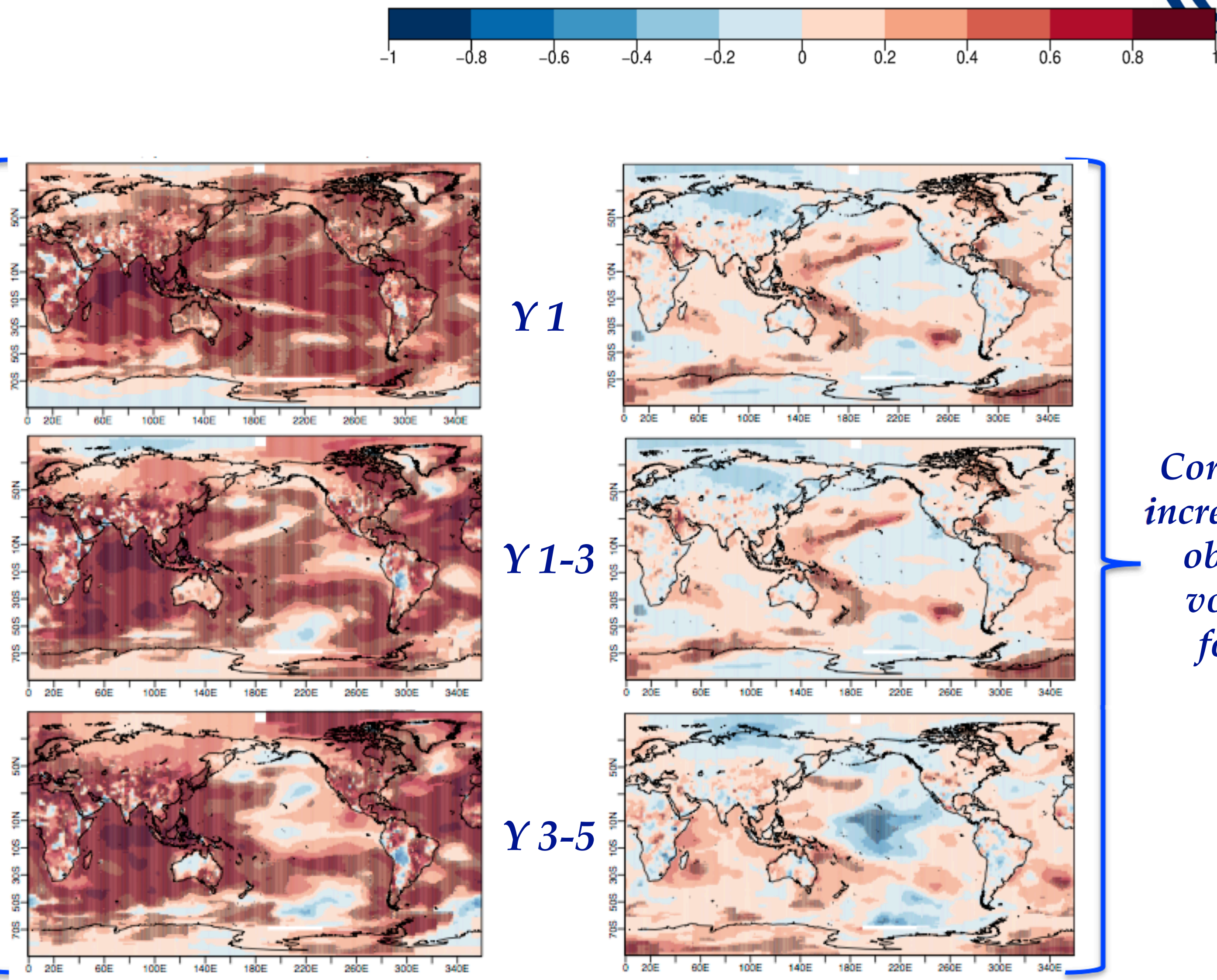


Y 1

Y 1-3

Y 3-5

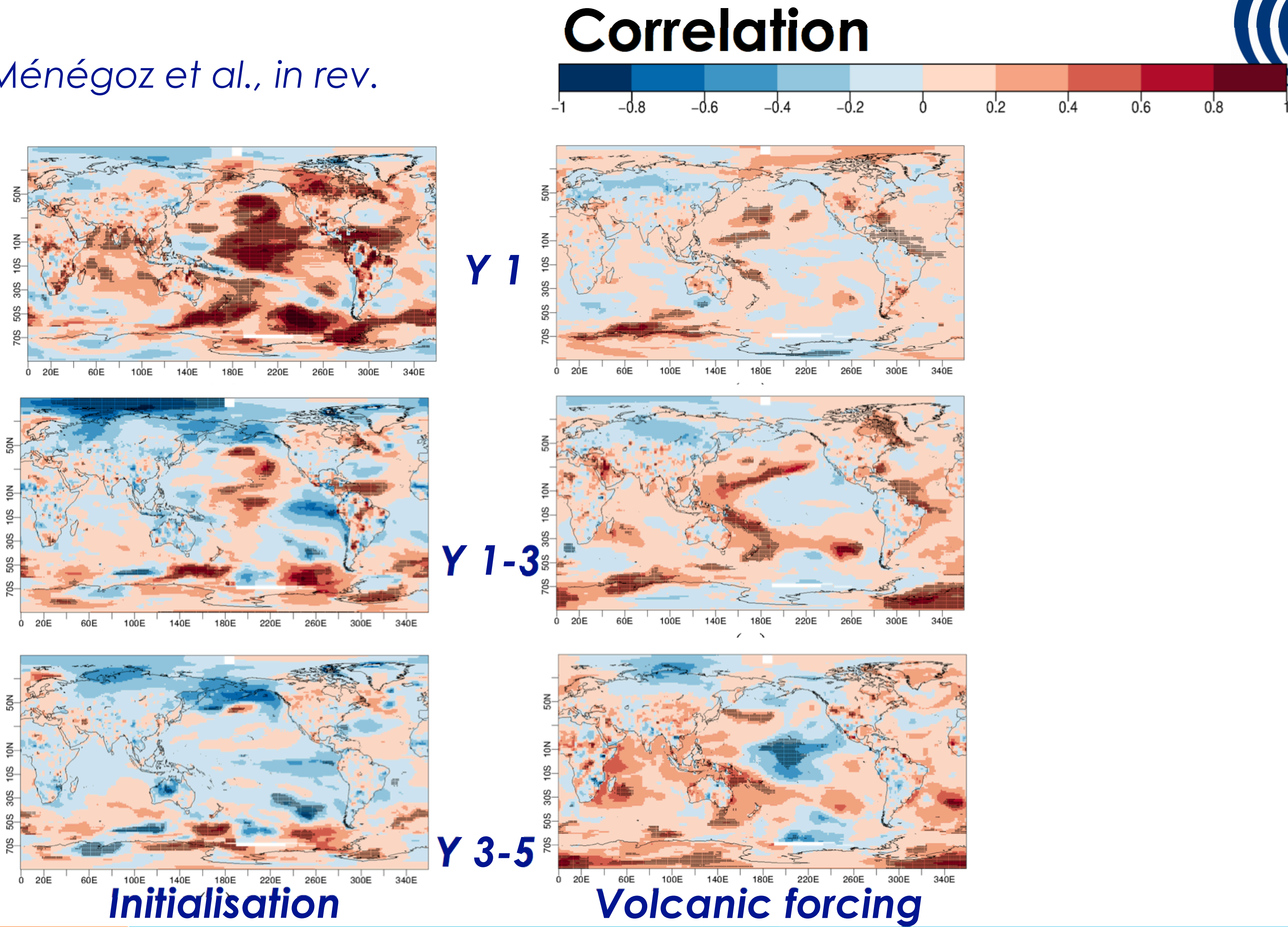
Correlation



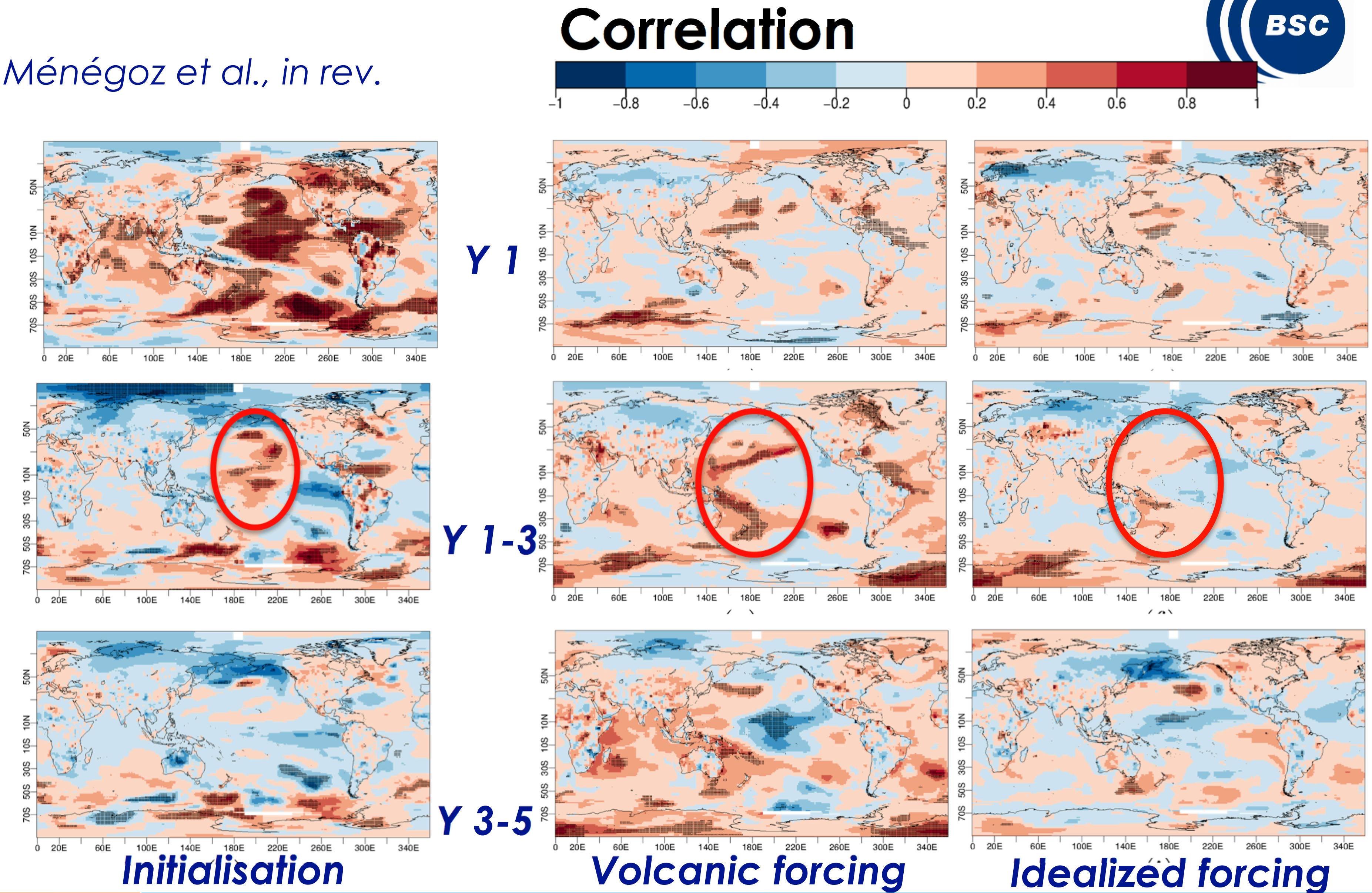
Correlation with initialisation and volcanoes

Correlation increase with observed volcanic forcing

Ménégoz et al., in rev.



Ménégoz et al., in rev.



Can we forecast the climate response to volcanic eruptions?

→ EC-Earth reproduces correctly the cooling occurring over large areas

→ Possibility to use idealized forcing or previous forcing for the next eruption

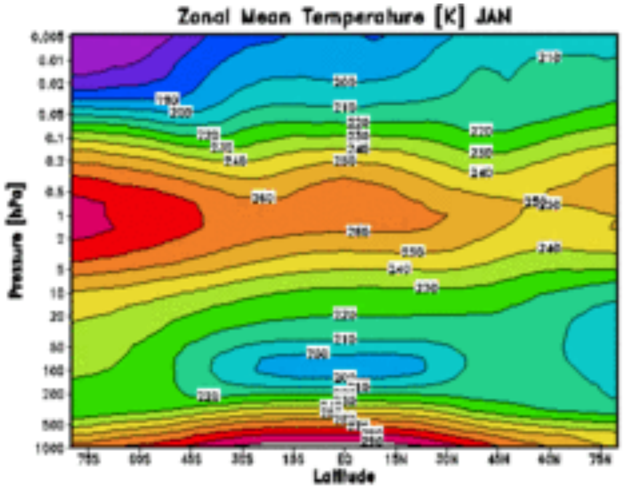
→ Dynamical signals partially overwhelmed by internal variability. ENSO and NAO skill mainly related to initialisation.

- Ménégoz, M., Bilbao, R., Bellprat, O., Guemas, V., Doblas-Reyes, F.J., Forecasting the climate response to volcanic eruptions, in revision for Environmental Research Letters.

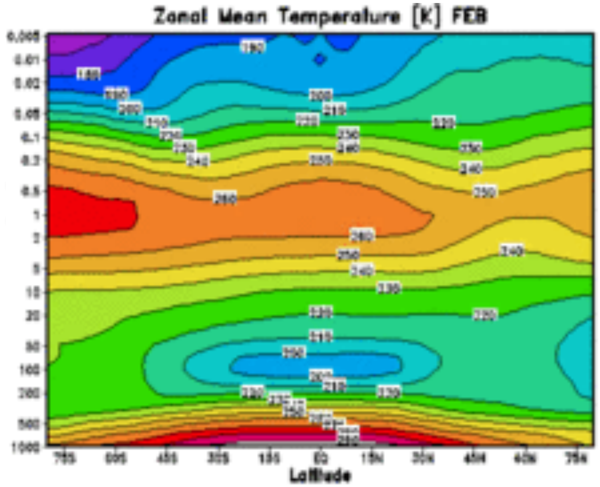
Thank you

Stratospheric observations

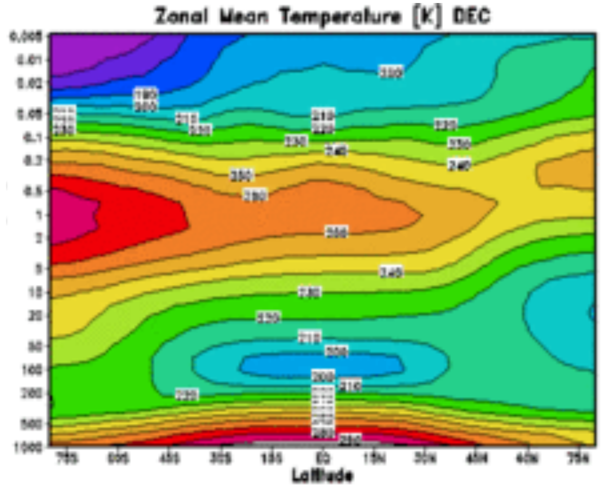
Climatology of the zonal mean of temperature:



January



February



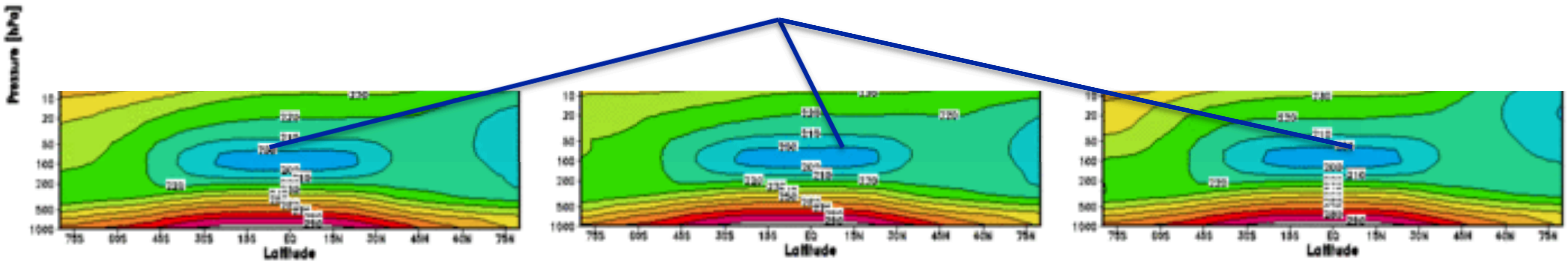
March

SPARC dataset (http://www.sparc-climate.org/)

Stratospheric observations

Climatology of the zonal mean of temperature:

At 100 hPa, the stratosphere is cooler in the Tropics than in the high latitudes



January February March

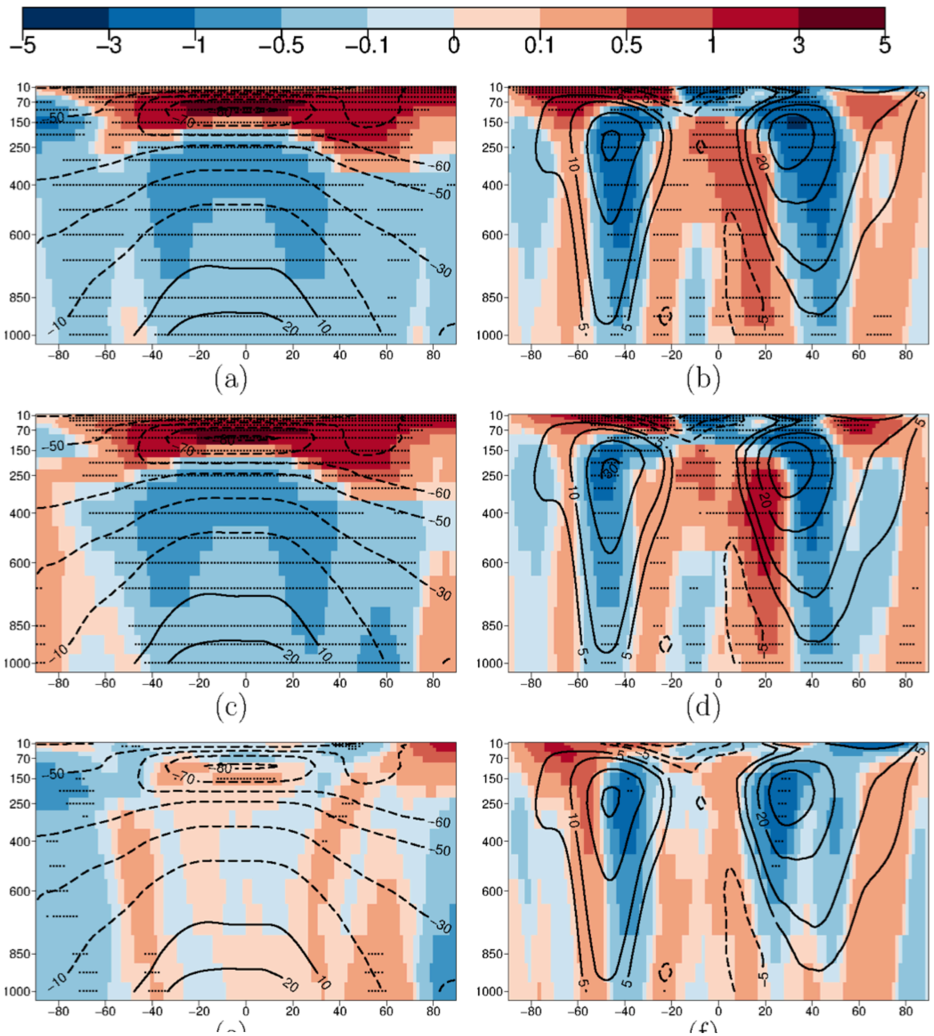
SPARC dataset (http://www.sparc-climate.org/)

Volcanic signal – first winter

Cold AMO

Warm AMO

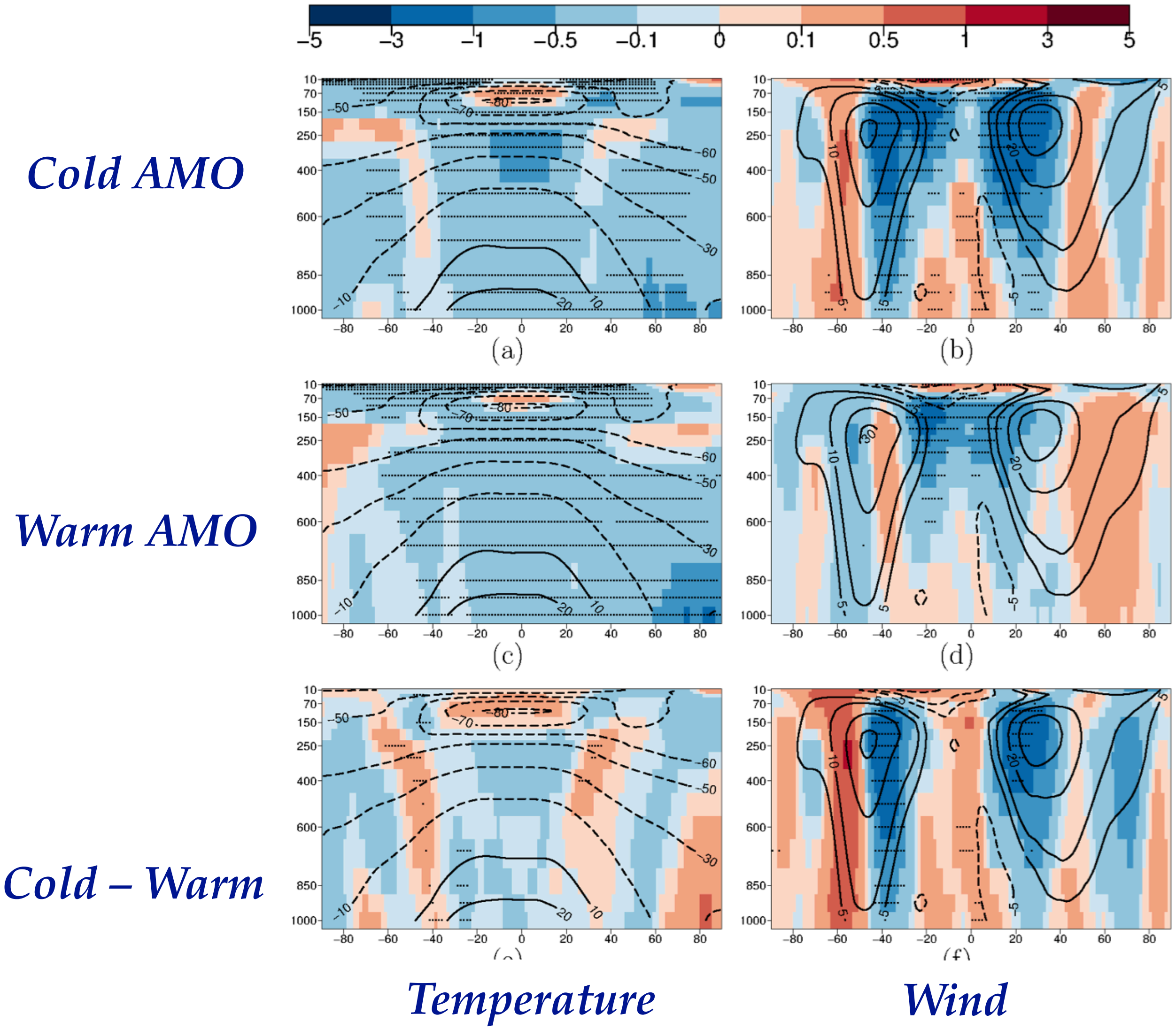
Cold – Warm



Temperature *Wind*

Zonal mean anomalies simulated the first winter after a volcanic eruption of temperature (°C, left) and wind (m.s-1, right)

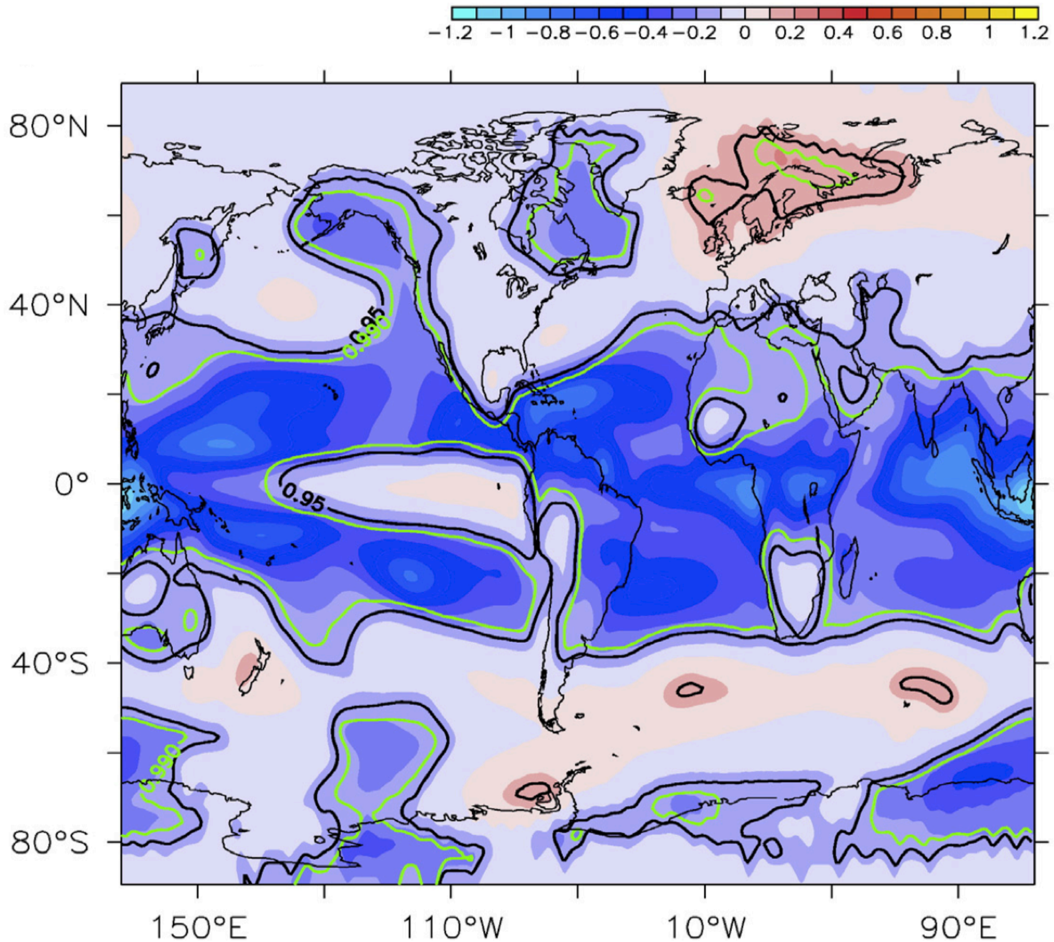
Volcanic signal – third winter



Zonal mean anomalies simulated the third winter after a volcanic eruption of temperature (°C, left) and wind (m.s-1, right)

Introduction

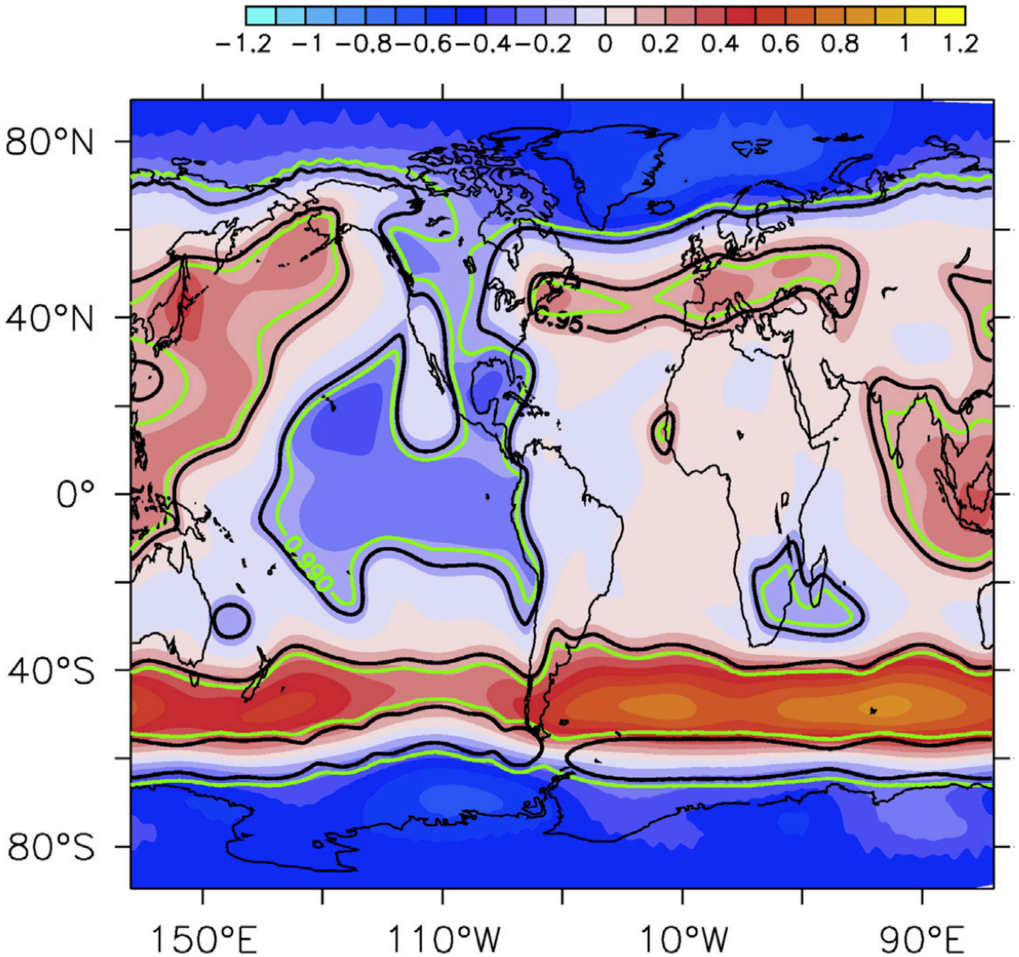
→ **Regional variations of the cooling: dynamical response?**



Composite of two-meter temperature modelled with CNRM-CM3 for the 19 eruptions larger or equal to the Pinatubo over the last millennium, in terms of the duration of the aerosol imprint in the atmosphere. (Swingedouw et al., 2017)

Introduction

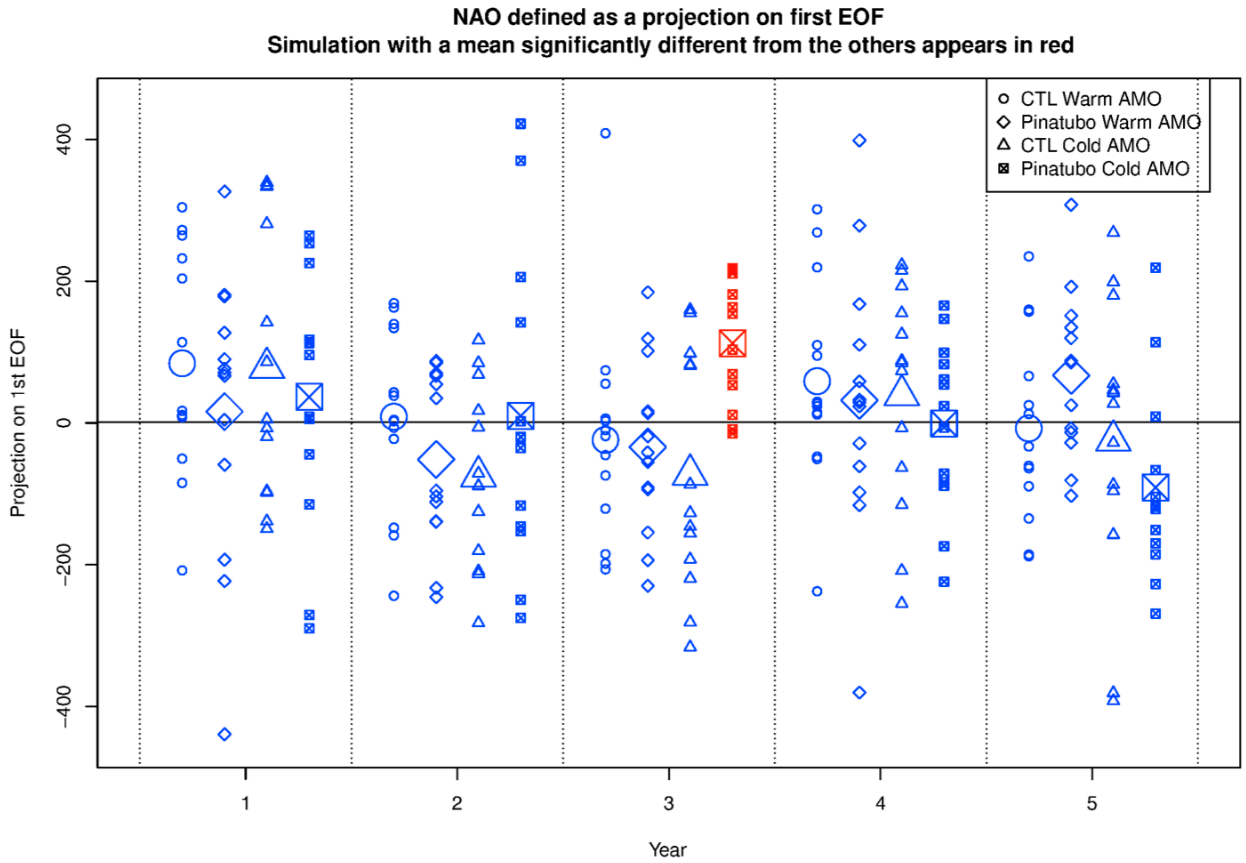
→ Regional variations of the cooling: dynamical response?



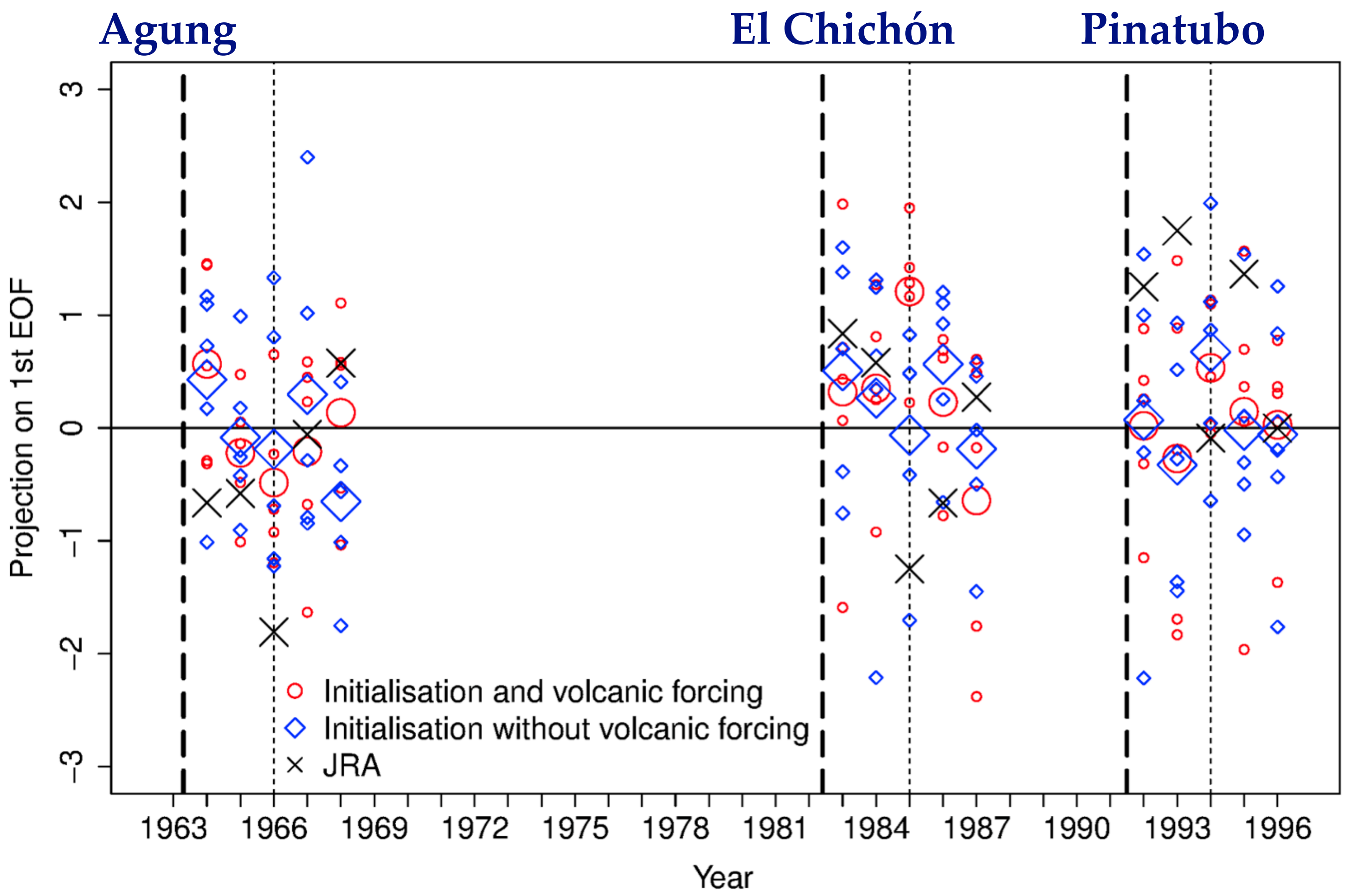
Composite of sea-level pressure modelled with CNRM-CM3 for the 19 eruptions larger or equal to the Pinatubo over the last millennium, in terms of the duration of the aerosol imprint in the atmosphere. (Swingedouw et al., 2017)

NAO and AMV

→ **Simulating a Pinatubo under warm/cold phases of the AMV (Perfect model approach with the CNRM-CM5 model)**

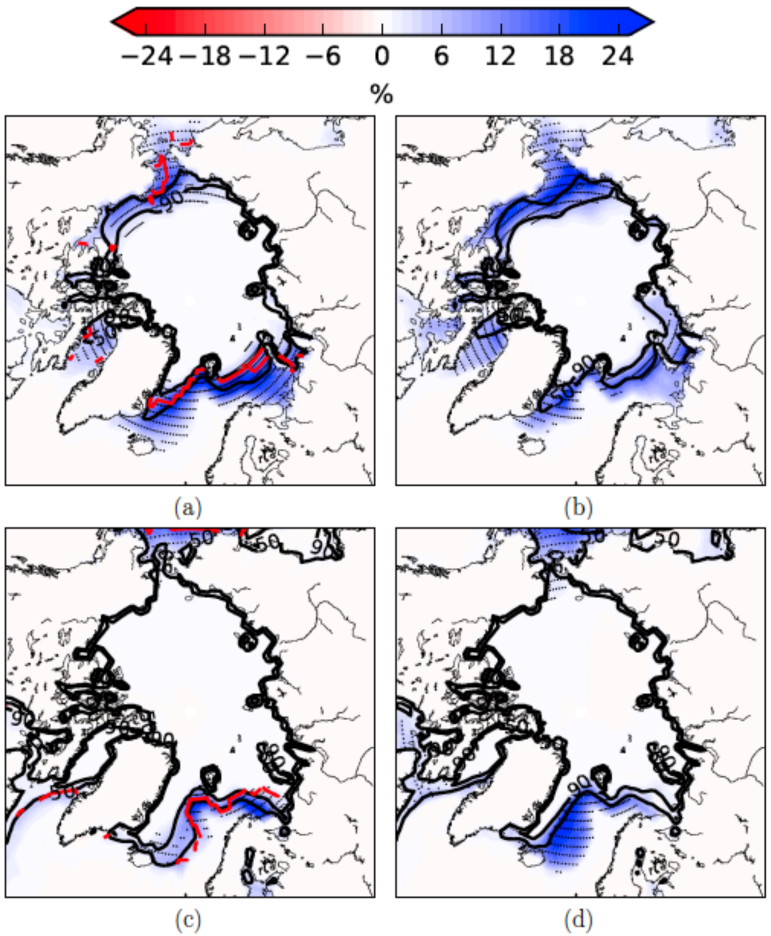


Significant NAO+ signal the third winter after a Pinatubo eruption under a cold AMV



EC-Earth forecasts (colour) and observations (black) of the North Atlantic Oscillation (NAO) index after the last major volcanic eruptions

Sea-ice anomalies



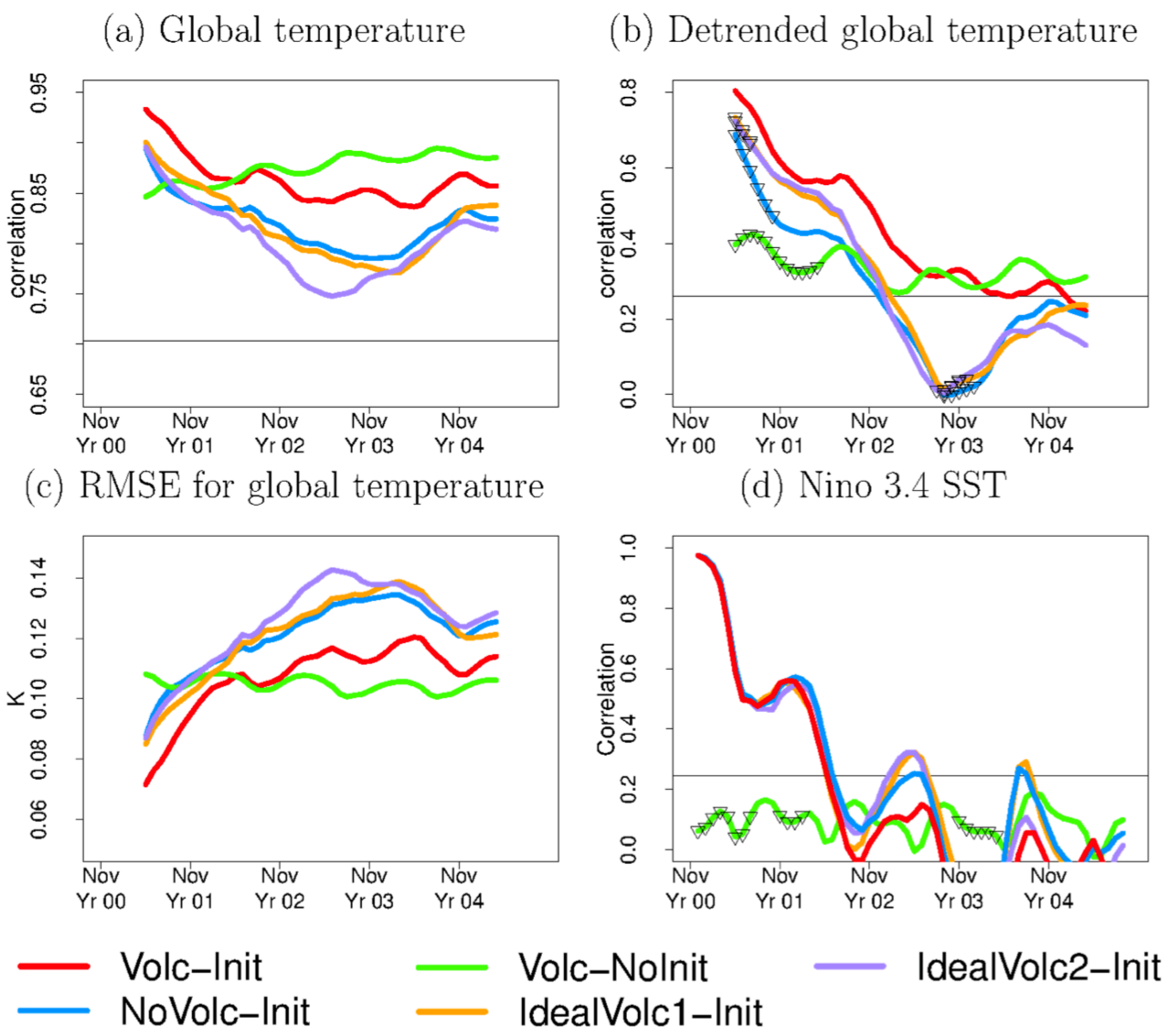
Autumn

Winter

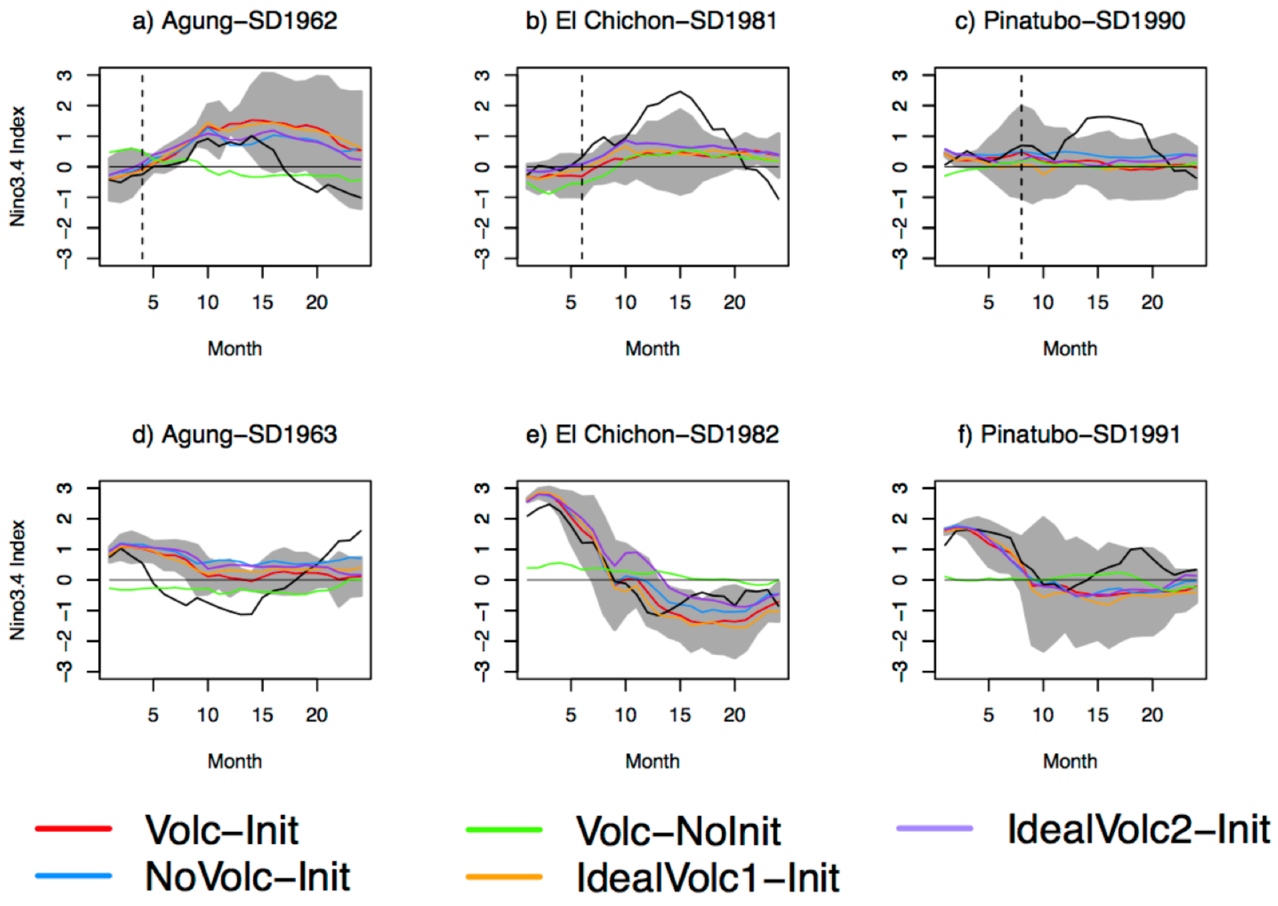
Cold AMO *Warm AMO*

Sea-ice anomalies simulated the third autumn and winter after a Pinatubo eruption. South of the red line, the response is stronger in the case of the cold AMO situation

Forecast skill

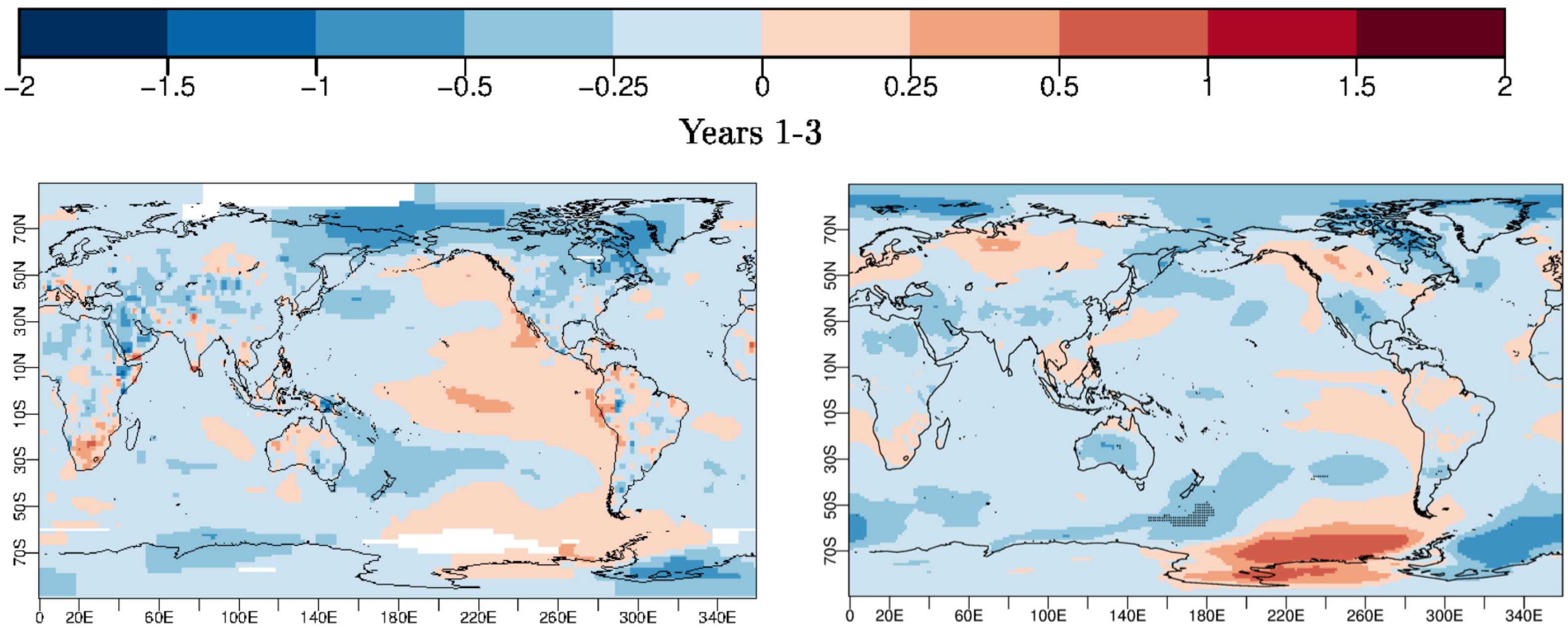


Forecast Anomalies: ENSO



Climate response to volcanoes

→ Large inter-annual variability partly overwhelms the volcanic signal

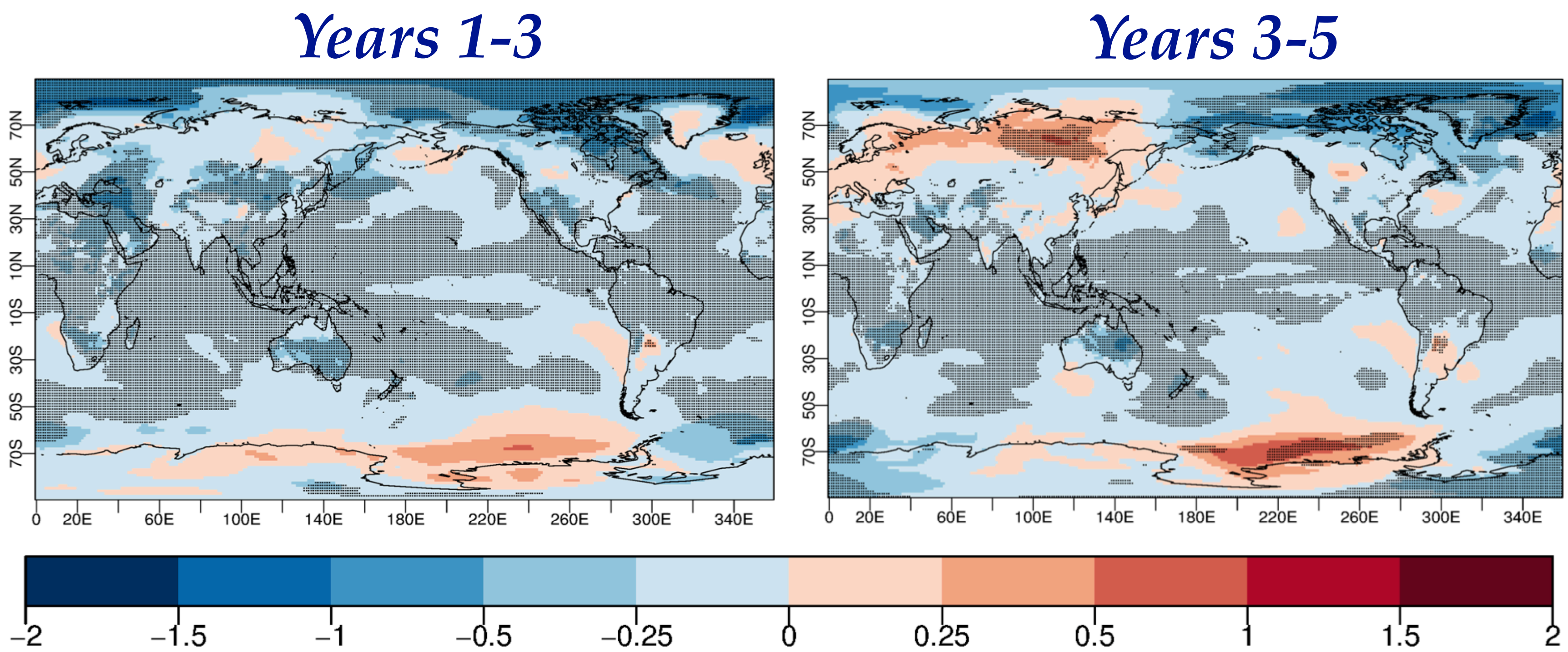


(a) Observation *(b) Model*

Surface temperature anomalies over forecast years 1-3 after the last 3 major eruptions: (a) Observation; (b) EC-Earth hindcasts. Anomalies are averaged over 3 start dates (and 5 members for the simulations). Shaded areas show regions with significant differences with a 5% level, areas without observations appear in white.

Climate response to volcanoes

Sensitivity experiment with - without volcanoes



Surface temperature difference (°C). 3-year average after the 3 last major eruptions (Agung, 1963, Chichon, 1982 and Pinatubo, 1991). Difference has been computed between two 5-members hindcasts, one including and another excluding volcanic forcing of large eruptions, and appears shaded when significant with a 5% level.